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THE VELOCITY OF SOUND IN SEA WATER AT ZERO DEPTH

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ABSTRACT

The velocity of sound has been measured in natural sea water samples at megacycle frequencies by means of modern interferometric techniques. From these measurements, an empirical equation has been formulated, and new tables and graphs of the velocity of sound in natural sea water at "zero" depth are presented on the basis of this equation.

The validity of utilizing these velocity tables at sonar frequencies is based on theoretical work which indicates the error introduced by so doing is at least an order of magnitude smaller than the claimed accuracy. The accuracy of these tables is estimated to be within ±0.2 meter per second. The velocity values range approximately 2-4 meters per second higher than those in existing tables.

PROBLEM STATUS

This is an interim report; work on the general project is continuing.

AUTHORIZATION

NRL Problem S02-04
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CONTENTS

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INTRODUCTION

An accurate knowledge of the velocity of sound in sea water as a function of temperature, chemical composition (salinity and dissolved gas content), and pressure (depth) is essential to sonar–not only for ranging determinations but for calculation of possible refraction which may operate either to channel the sound energy or to send this energy into the ocean depths.

Available tables for the calculation of sound velocity in the ocean are based either on theoretical computations or radio-acoustic ranging (1-5). These latter field measurements, however, assume the existence of homogeneous water between two distant points. The theoretical tables use compressibility and density determinations made over forty years ago and assume the temperature dependence of specific heat for distilled water to be the same as for sea water.

Kuwahara's tables (3), calculated from empirical formulas for the compressibility of sea water, are as accurate as any, and are generally used in this country. These tables have been graphically presented (6), and used by the Naval Research Laboratory. A comparison of velocity values obtained from various tables is made for "normal" sea water of 35 parts per thousand (ppt or $^{0}/_{00}$) salinity in Table 1.*

BACKGROUND

Preliminary measurements of sound velocity in sea water with a less accurate instrument (7) (i.e., ±1 m/sec) indicated that Kuwahara's tables yield velocities that are too low by 3-4 m/sec. The Revised British Admirality Tables (4) yield velocities slightly lower than Kuwahara's. Kuwahara claims an accuracy of 3 m/sec for his tables, but the preliminary evidence seemed to indicate that his error is systematic and that his values are consistently low. More information was desired to check the need for revision of sound velocity tables.

The ultrasonic interferometers in present use at the Naval Research Laboratory, capable of measuring the velocity of sound in liquids to a precision of 1 part in 10,000, were chosen as ideal instruments for checking the existing tables.

EXPERIMENTAL PROCEDURE

Samples of sea water were obtained from the Bermuda-Key West area by various field parties from the Sound Division, NRL. Of the samples received, three were selected

*Tables and figures are grouped after the text.

on the basis of clarity and freedom from foreign material. Data concerning these samples will be found in Table 2. The samples were received within one to four days after collection, and their sound velocity was determined with a one-megacycle ultrasonic interferometer as soon as received, and at intervals throughout the investigation. Chlorinities were determined by the Mohr method of $AgNO_3$ titration using a special elongated-scale burette made by the Machlett Company and patterned after a modification of the original Mohr burette suggested by the Woods Hole Oceanographic Institution. Toward the end of this investigation a potentiometric titration with the Beckman automatic titrator and a Ag-AgCl electrode in conjunction with a calomel reference electrode was developed. This technique frees the operator from the close control required as the end point is approached, and eliminates the human factor in choosing the relatively difficult to determine colorimetric end point.

The temperature of the interferometer bath was controlled by Magna-Set thermoregulators adjusted to better than $\pm 0.01^\circ$ C by means of a Leeds and Northrup 8160 Platinum Resistance Thermometer in conjunction with an L&N G-1 Mueller Bridge and an L&N 2430-A galvanometer. The interferometer cell temperature was determined by Bureau of Standards calibrated mercury-in-glass thermometers which could be estimated to $\pm 0.02^\circ$ C.

To obtain various salinities in the range 19-41 parts per thousand, the natural sea water samples were diluted with distilled water and evaporated under vacuum. The chlorinity of each of the solutions was actually determined by Mohr titration in the same manner as the chlorinities of the original samples. The salinities were calculated by the empirical relationship established by an International Commission (8). This relationship is

$$\text{Salinity} = 0.03 + 1.805 \times \text{Chlorinity}.$$

Sound velocities in the various sea water samples obtained by the above method were determined over a temperature range of 0° to 40° C. The measurements were made at a one-megacycle frequency, but several determinations were made at three megacycles.

RESULTS AND DISCUSSION

The experimental determinations of sea water sound velocity were plotted in two series of graphs (not given here), velocity vs. temperature with salinity parameter and velocity vs. salinity with temperature parameter. The points in the latter graph formed straight lines for individual temperatures. From this graph, velocity values at integral temperatures and salinities were read to ± 0.1 meter per second. These values were then processed by the method of least squares to yield the following empirical equation for the velocity of sound in sea water over a range of salinities from 19-41 parts per thousand and a range of temperatures from 0° to 40° C.

$$V_m = 1448.6 + 4.618\, t_c - .0523\, t_c^2 \overset{?}{+} .00023\, t_c^3$$
$$+ 1.25\,(S-35) - .011\,(S-35)\,(t_c) + .0027 \times 10^{-5}\,(S-35)\, t_c^4$$
$$- 2 \times 10^{-7}\,(S-35)^4\,(1 + .577\, t_c - .0072\, t_c^2)$$

The last term of this equation becomes significant as salinity approaches zero, and yields velocities in agreement with experimental values for distilled water ($S = 0\,‰$). However, as no determinations were made from 0-19 parts per thousand salinity, the use of this equation in this range of salinities is not recommended. In Table 3 the experimental determinations of velocity are compared with the velocities corresponding to the same physical conditions obtained by the use of the empirical equation.

No significant difference was observed between the three natural sea water samples obtained from different locations when their measured velocities were compared with the sound velocities obtained by use of the empirical equation. No change in measured sound velocity was detected in any of the natural sea water samples over an approximately two-week period after receipt.

Table 4 is a comparison of velocity values obtained from Kuwahara's tables and the empirical equation.

Figure 1 and Figures 1a-g are graphical representations of this equation in metric units and Figure 2 and Figures 2a-p are the same graphs in British units. Figures 3 and 4 show the temperature dependence of the salinity coefficient of velocity in metric and British units respectively, together with a comparison of Kuwahara's values.

Tables 5, 6, and 7 are the corrections to the velocity of sound in sea water of 35 parts per thousand salinity at 0° C temperature and "zero" depth ($V_{0^\circ C,\, 35\ ppt,\ Op}$ = 1448.6 m/sec) for changes in temperature and/or salinity.

Table 5 contains values of V_t, the temperature correction to the velocity of sound in sea water of 35 ppt salinity referred to a temperature of 0° C. Table 6 contains values of V_S, the salinity correction to the velocity of sound in sea water at 0° C temperature referred to a salinity of 35 ppt. Table 7 contains values of V_{St}, the combined salinity-temperature correction to the velocity of sound in sea water of 35 ppt salinity and 0° C temperature for any simultaneous changes of temperature and salinity. These tables are believed to yield values of sound velocity to the same degree of precision as the empirical equation, i.e., better than ±0.2 m/sec.

THE CONCEPT OF SALINITY

A word of caution is advisable in the physical interpretation of these tables. The concept of salinity has been established by an International Commission and salinity is defined as "the total amount of solid material in grams contained in one kilogram of sea water when all the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized" (8). It has been found that "regardless of the absolute concentration, the relative proportions of the different major constituents are virtually constant except in regions of high dilution (low salinity) where minor deviations may occur" (8). * Thus salinity is usually determined by measuring chlorinity, a defined term, now redefined to be made independent of changes in atomic weights thus: "The number giving the chlorinity in grams per kilogram of a sea water sample is identical with the number giving the mass in grams of 'atomic weight silver' just necessary to precipitate the halogens in 0.3285233 kilogram of the sea water sample." Because of changes in atomic weights, the original definition of chlorinity is now called the chlorine-equivalent. The chlorine-equivalent is the quantity determined by the $AgNO_3$ titration, and the ratio of chlorine-equivalent to chlorinity is at present 1.00045. Neither the chlorine-equivalent nor the chlorinity represent the actual amount of chlorine in a sea water sample; bromine and iodine, as well as chlorine, participate in the $AgNO_3$ titration, whereas fluorine does not. Neither does the salinity, by definition, represent the total quantity of dissolved solids in sea water. The technique of determining the defined salinity, however, yields reproducible results. The following empirical equation has been obtained (8) for the dissolved solids content

$$\Sigma\ {}^0/_{00} = 0.073 + 1.8110\ Cl\ {}^0/_{00}.$$

It can be shown that the total amount of dissolved solids is greater than the defined salinity.

*Not underlined in the original

The point to be brought forth here is that Knudsen's Hydrographical Tables (in widespread use by oceanographers) have been shown to hold very well over the normal range of the concentration of sea water but are not necessarily valid for highly diluted or concentrated sea water. The diluted samples (from the Baltic Sea) used in preparing Knudsen's tables had been diluted by river water containing relatively large quantities of dissolved solids. Thus, the equation relating salinity to chlorinity shows a salinity of 0.03 ppt for zero chlorinity. The salinity determined by titration of sea water that had been diluted by water containing a lesser quantity of dissolved solids would be smaller that that obtained from Knudsen's tables. Conversely, if the sea water were diluted with water containing a greater quantity of dissolved solids, the salinity obtained from Knudsen's tables would be too low.

The validity of the chlorinity-salinity-density relationships as established by the International Commission depends upon the ratios of the more abundant substances in sea water being virtually constant. However, "chlorinities" determined by titration of sea water diluted by melting sea ice were consistently higher than those computed from density measurements (10,11). In this case, the diluting water was essentially distilled water. The dependence of the Cl-S-density relations on the dissolved solids content of the diluting water and the restricted application of these relations to highly diluted water occurring naturally or prepared in the laboratory should be kept in mind.

The sea water samples used in this investigation were prepared by evaporation under vacuum or by dilution with distilled water of "mid-ocean" water. Previous work has shown the velocity of sound in sea water to be an approximately linear summation of the velocities of the components (7), and thus the validity of this work also depends on the constancy of the ratios of major constituents of sea water.

VALIDITY OF THESE MEASUREMENTS AT SONAR FREQUENCIES

A question arises concerning the validity of utilizing at sonar frequencies these velocity measurements obtained at megacycle frequencies. A relaxational phenomenon exists for sea water with a frequency of about 200 kc at 22.5 °C. It is true that a small dispersion of sound velocity accompanies a relaxational absorption, but the generally accepted work of Kneser (13) shows this dispersion to be very small indeed. He gives the expression

$$V_\infty^2 - V_0^2 = \frac{2}{\pi}\,\alpha_m^* V_0 V_\infty$$

where V_0 is the sound velocity at very low frequency, V_∞ is the sound velocity at very high frequency, and α_m^* is the maximum value of the amplitude coefficient of absorption per wavelength for the relaxational frequency N_m. This can be written approximately as

$$\frac{V_\infty - V_0}{V} \cong \frac{\alpha_m^*}{\pi} .$$

Using the approximate value of 50×10^{-6} obtained by Wilson (12) for α_m^* and 1.5×10^5 cm/sec for V, $V_\infty - V_0 \cong 0.024$ meter/sec, a value which is well within experimental error.

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TABLES AND FIGURES

TABLE 1
Velocity of Sound in Sea Water
(from various tables)

Depth (m)	Temp. (°C)	Sal. (‰)	Velocity (m/sec)				
			Heck & Service	Wood	Br. Adm. 1927	Br. Adm. 1939	Kuwahara 1939
0	0	35	1450	1450	1445.3	1445.4	1445.5
0	10	35	1489	1488	1486.6	1486.7	1486.8
0	20	35	1514	1519	1518.6	1518.7	1518.7
0	30	35	--	1543	1543.0	1543.1	1543.2

TABLE 2
Sample Data

Sample No.	Date Collected	Date Received	Collection Location		Original Salinity (‰)	Temp. "in situ" (°C)	Exper. Salinity (‰)
			Lat.	Long.			
1	7/30/51	7/31/51	24°25′N	81°26′W	34.27	29	34.27
1	7/30/51	7/31/51	24°25′N	81°26′W	34.27	29	40.43
1	7/30/51	7/31/51	24°25′N	81°26′W	34.27	29	29.02
1	7/30/51	7/31/51	24°25′N	81°26′W	34.27	29	19.77
2	8/24/51	8/27/51	24°40′N	80°46′W	37.12	29	37.12
2	8/24/51	8/27/51	24°40′N	80°46′W	37.12	29	31.49
3	8/31/51	9/4/51	32°13′N	69°29′W	37.29	28	37.29
3	8/31/51	9/4/51	32°13′N	69°29′W	37.29	28	24.20

TABLE 3
Comparison of Experimental Determinations and Values from Empirical Equation

Salinity (‰)	Temperature (°C)	$V_{exp.}$ (m/sec)	$V_{eq.}$ (m/sec)	$V_{exp.}-V_{eq.}$ (m/sec)
40.43	40.0	1569.2	1569.1	+0.1
	30.2	1551.6	1551.8	-0.2
	20.0	1527.5	1527.5	0.0
	10.1	1496.5	1496.3	+0.2
	0.0	1455.3	1455.4	-0.1
37.29	39.1	1564.9	1565.0	-0.1
	30.0	1548.0	1548.2	-0.2
	25.0	1537.1	1537.2	-0.1
	20.0	1524.3	1524.3	0.0
	15.0	1509.5	1509.4	+0.1
	10.0	1492.5	1492.5	0.0
	5.0	1472.9	1473.2	-0.3
	0.0	1451.4	1451.5	-0.1
37.12	29.9	1547.7	1547.9	-0.2
34.27	40.0	1563.6	1563.6	+0.2
	30.0	1545.3	1545.5	-0.2
	20.0	1521.3	1521.1	+0.2
	10.0	1489.1	1489.0	+0.1
	0.0	1447.7	1447.7	0.0
31.49	40.0	1561.3	1561.2	+0.1
	30.0	1542.8	1542.6	+0.2
	20.0	1518.5	1518.3	+0.2
	10.0	1485.8	1485.8	0.0
	0.0	1444.2	1444.2	0.0
29.02	40.0	1558.9	1559.0	-0.1
	30.0	1540.5	1540.6	-0.1
	20.0	1515.9	1515.7	+0.2
	10.0	1483.1	1482.9	+0.2
	0.0	1441.1	1441.1	0.0
24.20	40.0	1554.8	1554.9	-0.1
	30.0	1536.1	1536.1	0.0
	20.0	1510.9	1510.8	+0.1
	10.0	1477.5	1477.5	0.0
	0.0	1434.9	1435.1	-0.2
19.77	40.0	1551.1	1551.0	+0.1
	30.0	1532.2	1531.9	+0.3
	20.0	1506.4	1506.2	+0.2
	10.0	1472.6	1472.5	+0.1
	5.0	1452.1	1452.2	-0.1
	0.0	1429.7	1429.6	+0.1
0	40.0	1529.5	1529.7	-0.2
	35.0	1520.9	1520.7	+0.2
	30.0	1509.9	1509.6	+0.3
	25.0	1496.8	1497.0	-0.2
	20.0	1483.1	1482.7	+0.4
	15.0	1466.5	1466.5	0.0
	10.0	1448.0	1448.0	0.0
	5.0	1427.0	1427.4	-0.4
0	0.0	--	1404.5	--

TABLE 4

Comparison of Velocity Values from Empirical Equations and Kuwahara's Tables

Temp (^{0}C)	Meters per Second					
	S = 31 ppt		S = 35 ppt		S = 39 ppt	
	Kuwahara	NRL	Kuwahara	NRL	Kuwahara	NRL
0	1440.3	1443.7	1445.5	1448.6	1450.7	1453.7
1	44.8	48.1	50.0	53.0	55.2	58.1
2	49.4	52.6	54.5	57.5	59.6	62.4
3	53.8	57.0	58.9	61.9	64.0	66.7
4	58.1	61.2	63.1	66.0	68.1	71.0
5	1462.3	1465.5	1467.3	1470.4	1472.3	1475.2
6	66.5	69.6	71.4	74.5	76.3	79.2
7	70.5	73.6	75.4	78.4	80.3	83.1
8	74.5	77.4	79.3	82.2	84.2	87.0
9	78.3	81.2	83.1	86.0	87.9	90.7
10	1482.0	85.1	1486.8	1488.8	1491.6	1494.4
11	85.7	88.7	90.4	93.4	95.1	97.9
12	89.2	92.2	93.9	97.0	98.6	1501.3
13	92.7	95.7	97.3	1500.3	1502.0	04.7
14	96.0	99.0	1500.6	03.6	05.2	08.0
15	1499.3	1502.4	1503.9	1506.9	1508.5	1511.2
16	1502.5	05.6	07.0	10.0	11.5	14.2
17	05.6	08.8	10.1	13.0	14.6	17.2
18	08.6	11.8	13.0	16.0	17.5	20.2
19	11.5	14.8	15.9	19.0	20.3	23.1
20	1514.3	1517.8	1518.7	1521.9	1523.1	1526.0
21	17.2	20.6	21.5	24.7	25.9	28.7
22	19.8	23.2	24.1	27.3	28.4	31.3
23	22.4	25.9	26.7	29.9	31.0	33.9
24	25.0	28.4	29.2	32.4	33.5	36.4
25	1527.5	1531.0	1531.7	1535.0	1535.9	1538.8
26	29.9	33.4	34.1	37.3	38.3	41.2
27	32.3	35.8	36.4	39.6	40.6	43.5
28	34.6	38.0	38.7	41.9	42.9	45.8
29	36.9	40.3	41.0	44.1	45.1	48.0
30	1539.1	1542.5	1543.2	1546.3	1547.3	1550.2

TABLE 5

Correction V_t to $V(0^0$ C, 35 ppt, Op) = 1448.6 m/sec for Changes in Temperature

T (^oC)	0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0	0.0	0.4	0.9	1.3	1.8	2.2	2.6	3.1	3.5	4.0
1	4.4	4.8	5.3	5.7	6.2	6.6	7.0	7.5	7.9	8.4
2	8.8	9.2	9.7	10.1	10.6	11.0	11.4	11.9	12.3	12.8
3	13.2	13.6	14.1	14.5	14.9	15.4	15.8	16.2	16.6	17.1
4	17.5	17.9	18.4	18.8	19.2	19.7	20.1	20.5	20.9	21.4
5	21.8	22.2	22.6	23.0	23.4	23.8	24.3	24.7	25.1	25.5
6	25.9	26.3	26.7	27.1	27.5	27.9	28.2	28.6	29.0	29.4
7	29.8	30.2	30.6	30.9	31.3	31.7	32.1	32.5	32.8	33.2
8	33.6	34.0	34.4	34.7	35.1	35.5	35.9	36.3	36.6	37.0
9	37.4	37.8	38.2	38.5	38.9	39.3	39.7	40.1	40.4	40.8
10	41.2	41.6	41.9	42.3	42.6	43.0	43.4	43.7	44.1	44.4
11	44.8	45.2	45.5	45.9	46.2	46.6	47.0	47.3	47.7	48.0
12	48.4	48.7	49.1	49.4	49.7	50.0	50.4	50.7	51.0	51.4
13	51.7	52.0	52.4	52.7	53.0	53.3	53.7	54.0	54.3	54.7
14	55.0	55.3	55.7	56.0	56.3	56.6	57.0	57.3	57.6	58.0
15	58.3	58.6	58.9	59.2	59.5	59.9	60.2	60.5	60.8	61.1
16	61.4	61.7	62.0	62.3	62.6	62.9	63.2	63.5	63.8	64.1
17	64.4	64.7	65.0	65.3	65.6	65.9	66.2	66.5	66.8	67.1
18	67.4	67.7	68.0	68.3	68.6	68.9	69.2	69.5	69.8	70.1
19	70.4	70.7	71.0	71.3	71.6	71.8	72.1	72.4	72.7	73.0
20	73.3	73.6	73.9	74.1	74.4	74.7	75.0	75.3	75.5	75.8
21	76.1	76.4	76.6	76.9	77.1	77.4	77.7	77.9	78.2	78.4
22	78.7	79.0	79.2	79.5	79.7	80.0	80.3	80.5	80.8	81.0
23	81.3	81.5	81.8	82.1	82.3	82.5	82.8	83.1	83.3	83.5
24	83.8	84.0	84.3	84.6	84.8	85.0	85.3	85.6	85.8	86.0
25	86.3	86.5	86.8	87.0	87.3	87.5	87.7	88.0	88.2	88.5
26	88.7	88.9	89.2	89.4	89.6	89.9	90.1	90.3	90.5	90.8
27	91.0	91.2	91.5	91.7	91.9	92.2	92.4	92.6	92.8	93.1
28	93.3	93.5	93.7	94.0	94.2	94.4	94.8	94.8	95.1	95.3
29	95.5	95.7	95.9	96.2	96.4	96.6	96.8	97.0	97.3	97.5
30	97.7	97.9	98.1	98.3	98.5	98.7	99.0	99.2	99.4	99.6
31	99.8	100.0	100.2	100.4	100.6	100.8	101.1	101.3	101.5	101.7
32	101.9	102.1	102.3	102.5	102.7	102.9	103.2	103.4	103.6	103.8
33	104.0	104.2	104.4	104.6	104.8	105.0	105.2	105.4	105.6	105.8
34	106.0	106.2	106.4	106.6	106.8	107.0	107.1	107.3	107.5	107.7
35	107.9	108.1	108.3	108.4	108.6	108.8	109.0	109.2	109.3	109.5
36	109.7	109.9	110.1	110.2	110.4	110.6	110.8	111.0	111.1	111.3
37	111.5	111.7	111.8	111.9	112.1	112.3	112.4	112.5	112.7	112.9
38	113.0	113.2	113.3	113.4	113.6	113.8	113.9	114.0	114.2	114.4
39	114.5	114.6	114.7	114.9	115.0	115.1	115.2	115.3	115.5	115.6
40	115.7									

TABLE 6

Correction V_s to $V_{(0^\circ C,\ 35\ ppt,\ Op)} = 1448.6$ m/sec for Changes in Salinity

Salinity (°/oo)	0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0*	-43.8									
19*	-20.0	-19.9	-19.8	-19.6	-19.5	-19.4	-19.2	-19.1	-19.0	-18.9
20	-18.8	-18.6	-18.5	-18.4	-18.2	-18.1	-18.0	-17.9	-17.8	-17.6
21	-17.5	-17.4	-17.2	-17.1	-17.0	-16.9	-16.8	-16.6	-16.5	-16.4
22	-16.2	-16.1	-16.0	-15.9	-15.8	-15.6	-15.5	-15.4	-15.2	-15.1
23	-15.0	-14.9	-14.8	-14.6	-14.5	-14.4	-14.2	-14.1	-14.0	-13.9
24	-13.8	-13.6	-13.5	-13.4	-13.2	-13.1	-13.0	-12.9	-12.8	-12.6
25	-12.5	-12.4	-12.2	-12.1	-12.0	-11.9	-11.8	-11.6	-11.5	-11.4
26	-11.2	-11.1	-11.0	-10.9	-10.8	-10.6	-10.5	-10.4	-10.2	-10.1
27	-10.0	- 9.9	- 9.8	- 9.6	- 9.5	- 9.4	- 9.2	- 9.1	- 9.0	- 8.9
28	- 8.8	- 8.6	- 8.5	- 8.4	- 8.2	- 8.1	- 8.0	- 7.9	- 7.8	- 7.6
29	- 7.5	- 7.4	- 7.2	- 7.1	- 7.0	- 6.9	- 6.8	- 6.6	- 6.5	- 6.4
30	- 6.2	- 6.1	- 6.0	- 5.9	- 5.8	- 5.6	- 5.5	- 5.4	- 5.2	- 5.1
31	- 5.0	- 4.9	- 4.8	- 4.6	- 4.5	- 4.4	- 4.2	- 4.1	- 4.0	- 3.9
32	- 3.7	- 3.6	- 3.5	- 3.4	- 3.2	- 3.1	- 3.0	- 2.9	- 2.8	- 2.6
33	- 2.5	- 2.4	- 2.2	- 2.1	- 2.0	- 1.9	- 1.8	- 1.6	- 1.5	- 1.4
34	- 1.2	- 1.1	- 1.0	- 0.9	- 0.8	- 0.6	- 0.5	- 0.4	- 0.2	- 0.1
35	0.0	0.1	0.2	0.4	0.5	0.6	0.8	0.9	1.0	1.1
36	1.2	1.4	1.5	1.6	1.8	1.9	2.0	2.1	2.2	2.4
37	2.5	2.6	2.8	2.9	3.0	3.1	3.2	3.4	3.5	3.6
38	3.7	3.9	4.0	4.1	4.2	4.4	4.5	4.6	4.8	4.9
39	5.0	5.1	5.2	5.4	5.5	5.6	5.8	5.9	6.0	6.1
40	6.2	6.4	6.5	6.6	6.8	6.9	7.0	7.1	7.2	7.4
41	7.5									

*Interpolation between 0 °/oo and 19 °/oo salinity is not recommended.

TABLE 7

Correction V_{st} to $V(0^{\circ}$ C, 35 ppt, Op$)$ = 1448.6 m/sec for Simultaneous Changes in Salinity and Temperature

T ($^{\circ}$C)	$S^{0}/_{00}$ 0*	19*	21	23	25	27	29	31	33	35	37	39	41
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0
2	+ 0.9	+0.4	+0.3	+0.3	+0.3	+0.2	+0.1	+0.1	+0.1	0	-0.1	-0.1	-0.1
4	+ 2.0	+0.9	+0.8	+0.7	+0.5	+0.4	+0.3	+0.2	+0.1	0	-0.1	-0.2	-0.3
6	+ 2.8	+1.3	+1.1	+1.0	+0.8	+0.6	+0.5	+0.3	+0.2	0	-0.2	-0.3	-0.5
8	+ 3.7	+1.7	+1.5	+1.3	+1.1	+0.8	+0.6	+0.4	+0.2	0	-0.2	-0.4	-0.6
10	+ 4.4	+2.0	+1.7	+1.5	+1.3	+1.0	+0.7	+0.5	+0.3	0	-0.3	-0.5	-0.7
12	+ 5.3	+2.4	+2.1	+1.8	+1.4	+1.2	+0.9	+0.6	+0.3	0	-0.3	-0.6	-0.9
14	+ 6.2	+2.8	+2.5	+2.1	+1.7	+1.4	+1.1	+0.7	+0.3	0	-0.3	-0.7	-1.1
16	+ 6.9	+3.1	+2.7	+2.3	+1.9	+1.6	+1.2	+0.8	+0.4	0	-0.4	-0.8	-1.2
18	+ 7.6	+3.4	+3.0	+2.6	+2.1	+1.7	+1.3	+0.9	+0.4	0	-0.4	-0.9	-1.3
20	+ 8.4	+3.8	+3.4	+2.9	+2.4	+1.9	+1.4	+1.0	+0.5	0	-0.5	-1.0	-1.4
22	+ 9.2	+4.2	+3.6	+3.1	+2.6	+2.1	+1.6	+1.0	+0.5	0	-0.5	-1.0	-1.6
24	+ 9.7	+4.4	+3.9	+3.3	+2.7	+2.2	+1.7	+1.1	+0.5	0	-0.5	-1.1	-1.7
26	+10.4	+4.7	+4.1	+3.5	+2.9	+2.4	+1.8	+1.2	+0.6	0	-0.6	-1.2	-1.8
28	+10.9	+5.0	+4.3	+3.7	+3.1	+2.5	+1.9	+1.2	+0.6	0	-0.6	-1.2	-1.9
30	+11.4	+5.2	+4.5	+3.9	+3.3	+2.6	+1.9	+1.3	+0.7	0	-0.7	-1.3	-1.9
32	+12.0	+5.4	+4.8	+4.1	+3.4	+2.7	+2.0	+1.4	+0.7	0	-0.7	-1.4	-2.0
34	+12.3	+5.6	+4.9	+4.2	+3.5	+2.8	+2.1	+1.4	+0.7	0	-0.7	-1.4	-2.1
36	+12.6	+5.8	+5.0	+4.3	+3.6	+2.9	+2.2	+1.4	+0.7	0	-0.7	-1.4	-2.2
38	+13.0	+5.9	+5.2	+4.4	+3.7	+3.0	+2.2	+1.5	+0.7	0	-0.7	-1.5	-2.2
40	+13.2	+6.0	+5.3	+4.5	+3.7	+3.0	+2.3	+1.5	+0.7	0	-0.7	-1.5	-2.3

* Interpolation between 0 $^{0}/_{00}$ and 19 $^{0}/_{00}$ salinity is not recommended.

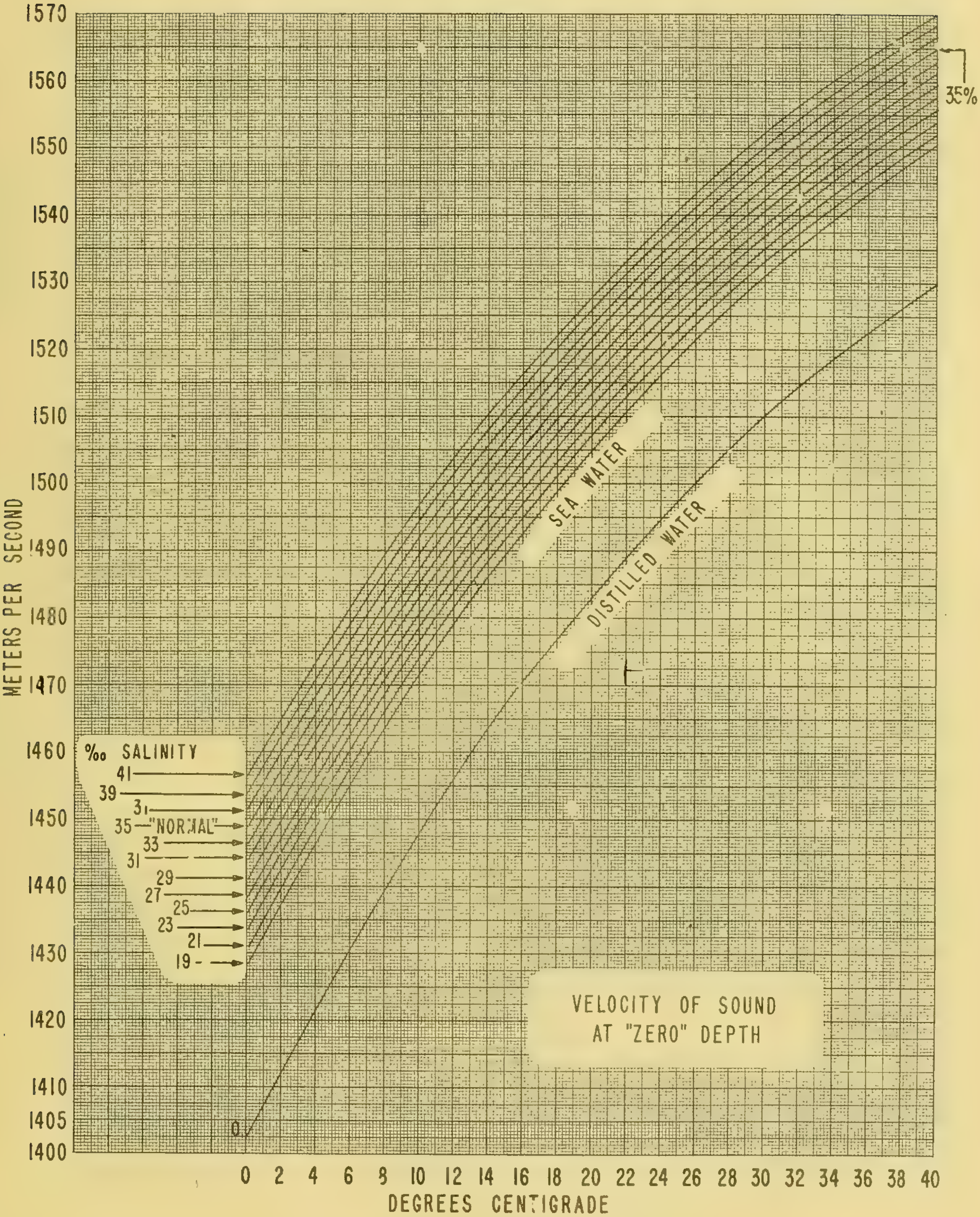

Figure 1 - Velocity of Sound at Zero Depth Metric Units

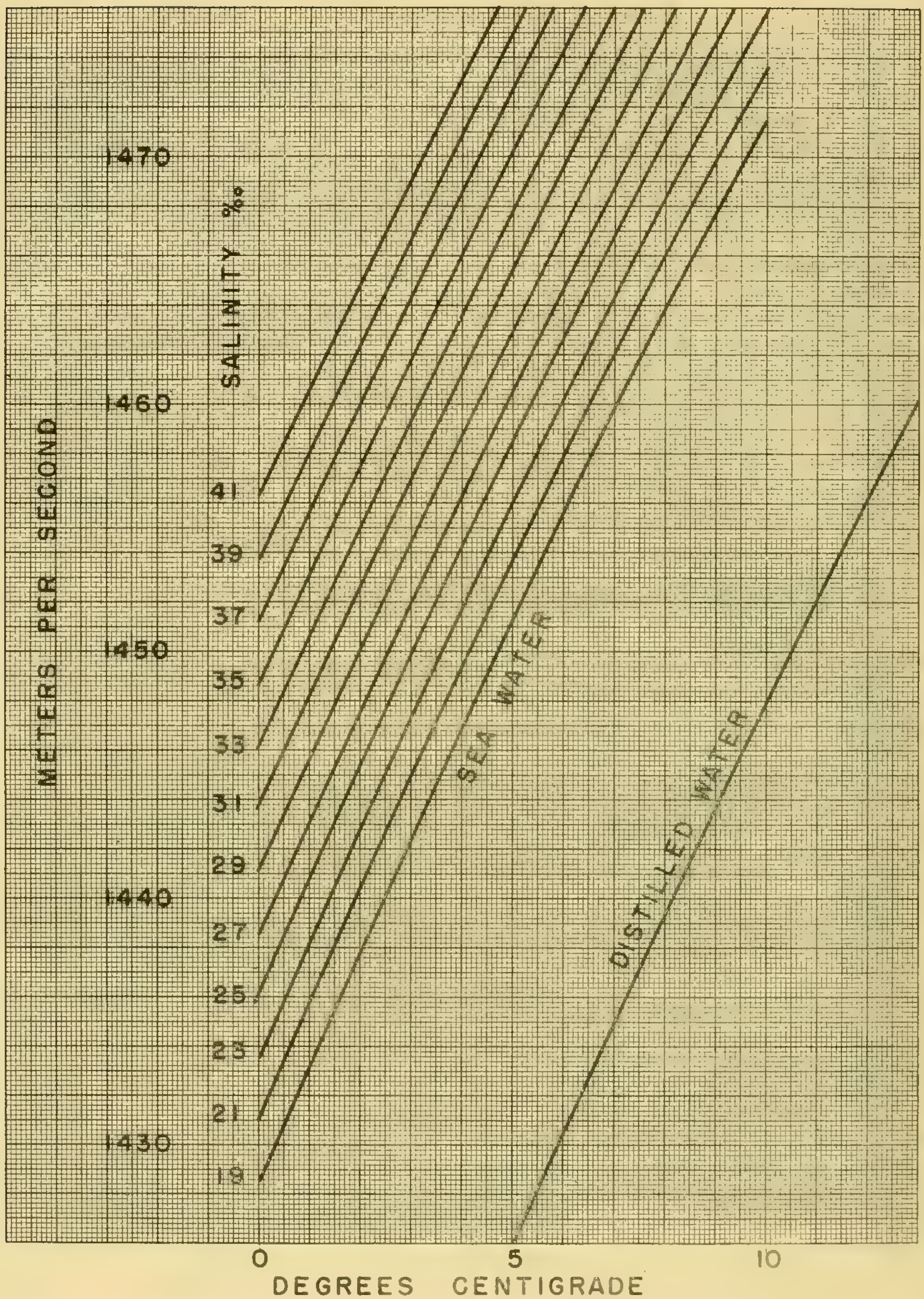

Figure 1-a

Figure 1 a-g - Velocity of Sound at Zero Depth Metric Units - Expanded Scale

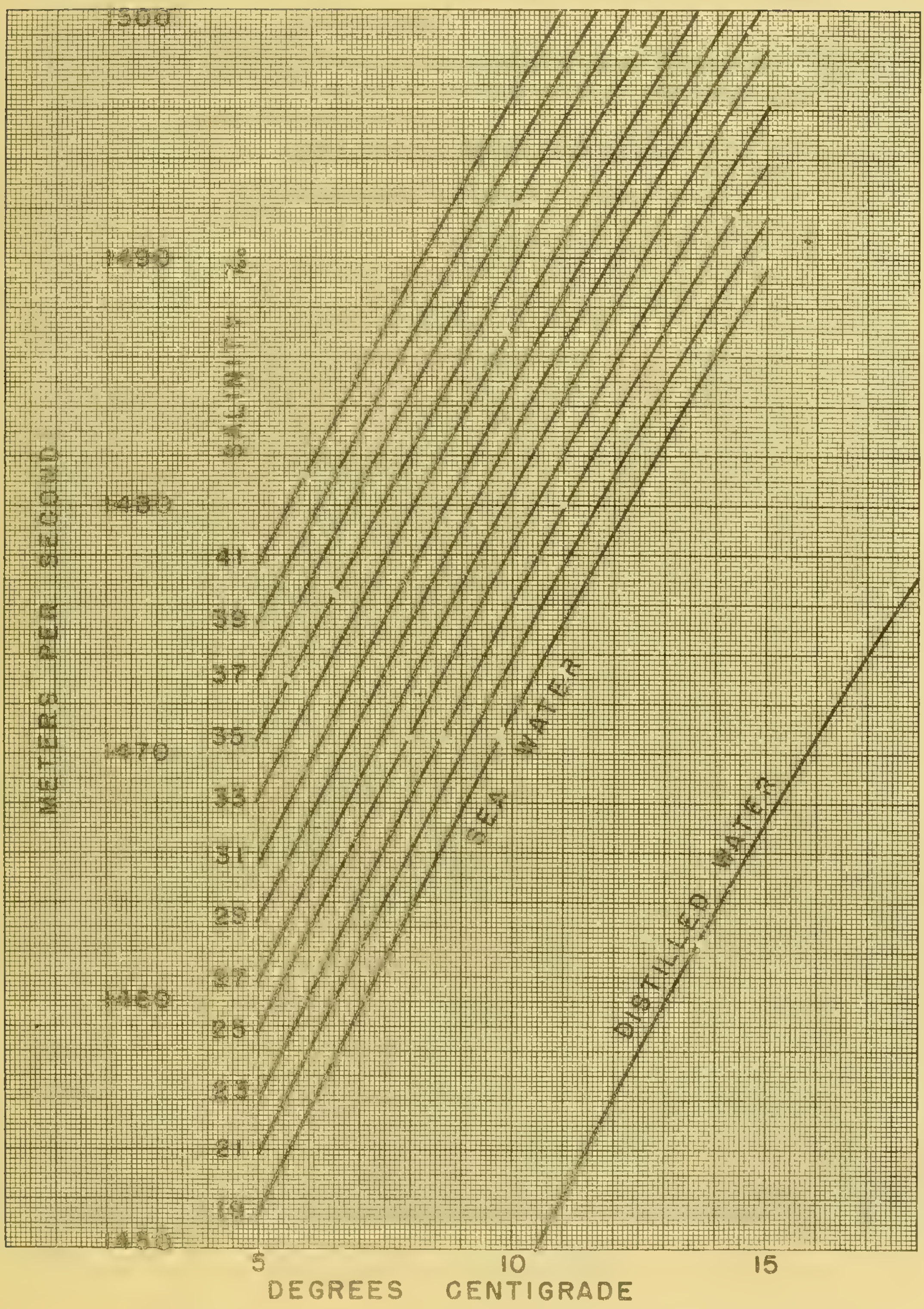
METERS PER SECOND
1500
1490
1480
1470
1460
1450
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
DISTILLED WATER
5
10
15
DEGREES CENTIGRADE

Figure 1-b

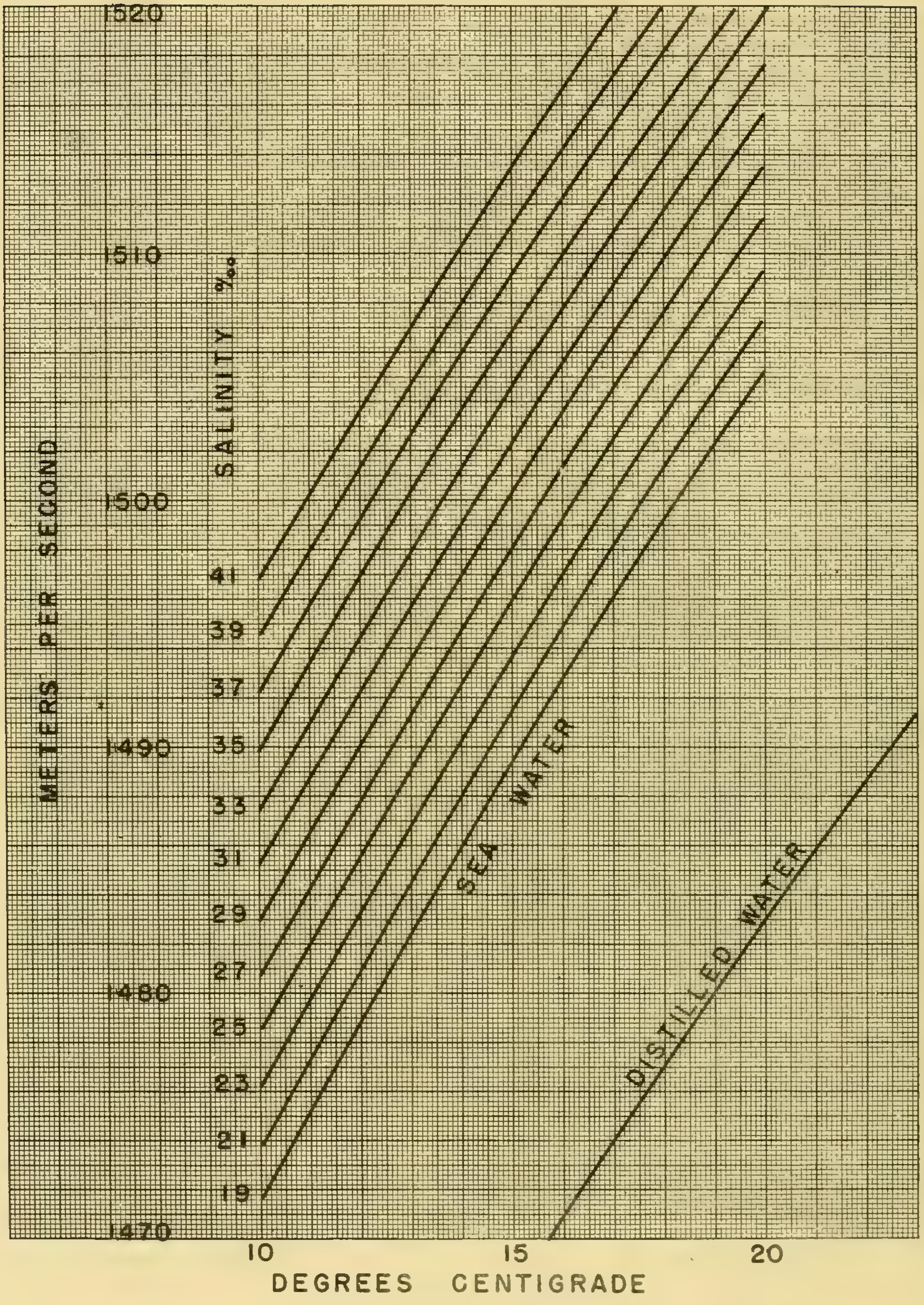
METERS PER SECOND
1520
1510
1500
1490
1480
1470
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
DISTILLED WATER
10
15
20
DEGREES CENTIGRADE

Figure 1-c

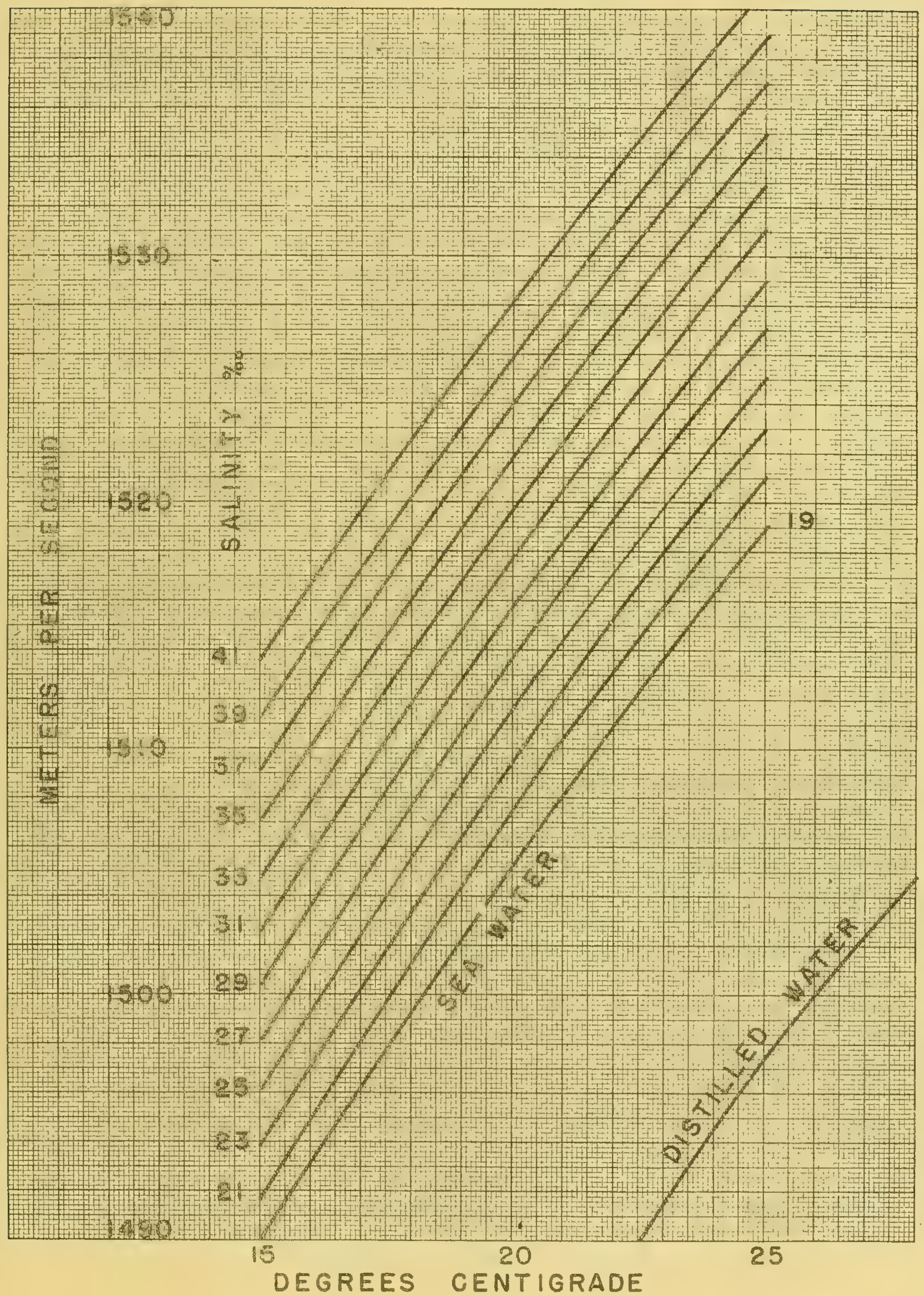
1540
1530
1520
1510
1500
1490
METERS PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
DISTILLED WATER
15
20
25
DEGREES CENTIGRADE

Figure 1-d

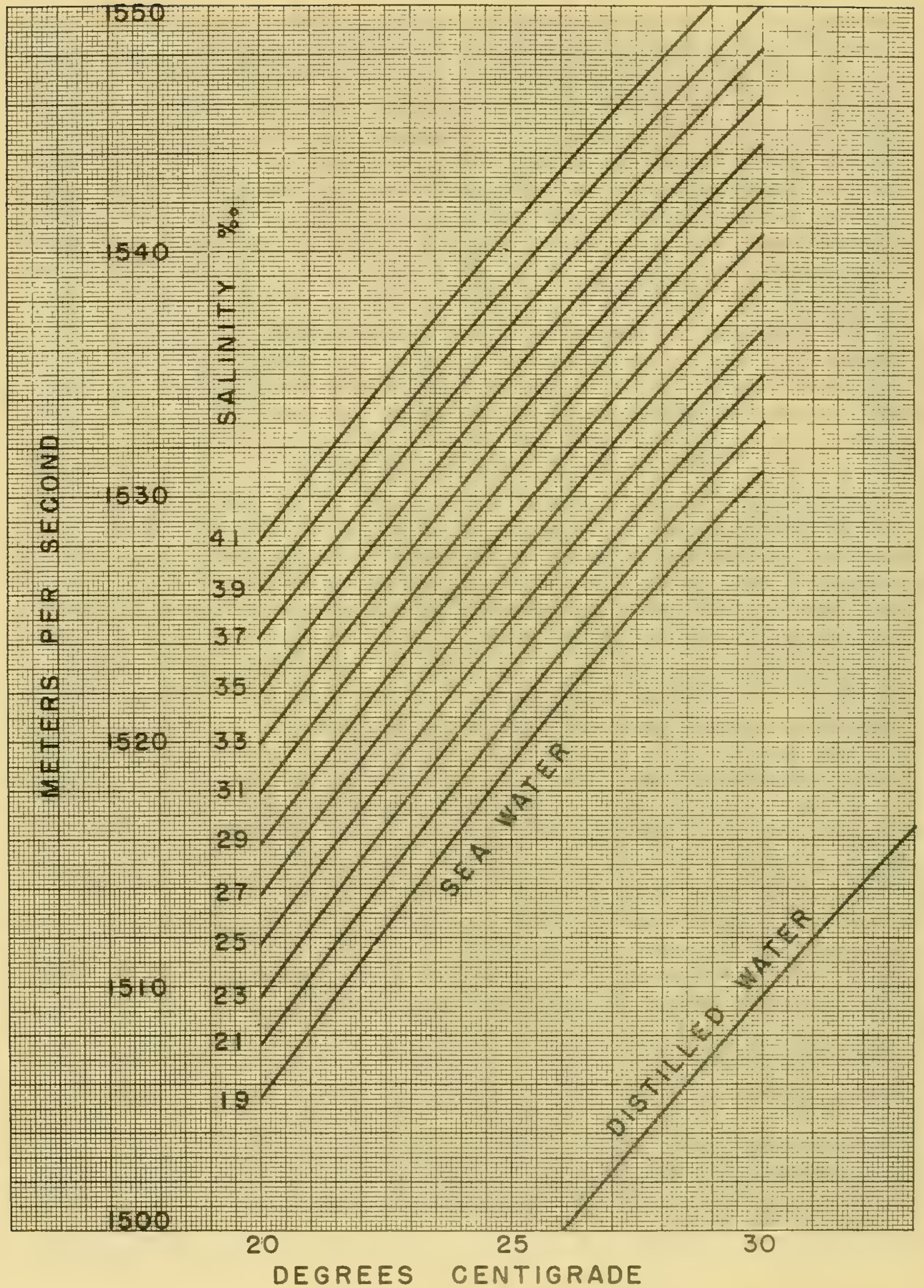
1550
1540
1530
1520
1510
1500
METERS PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
DISTILLED WATER
20
25
30
DEGREES CENTIGRADE

Figure 1-e

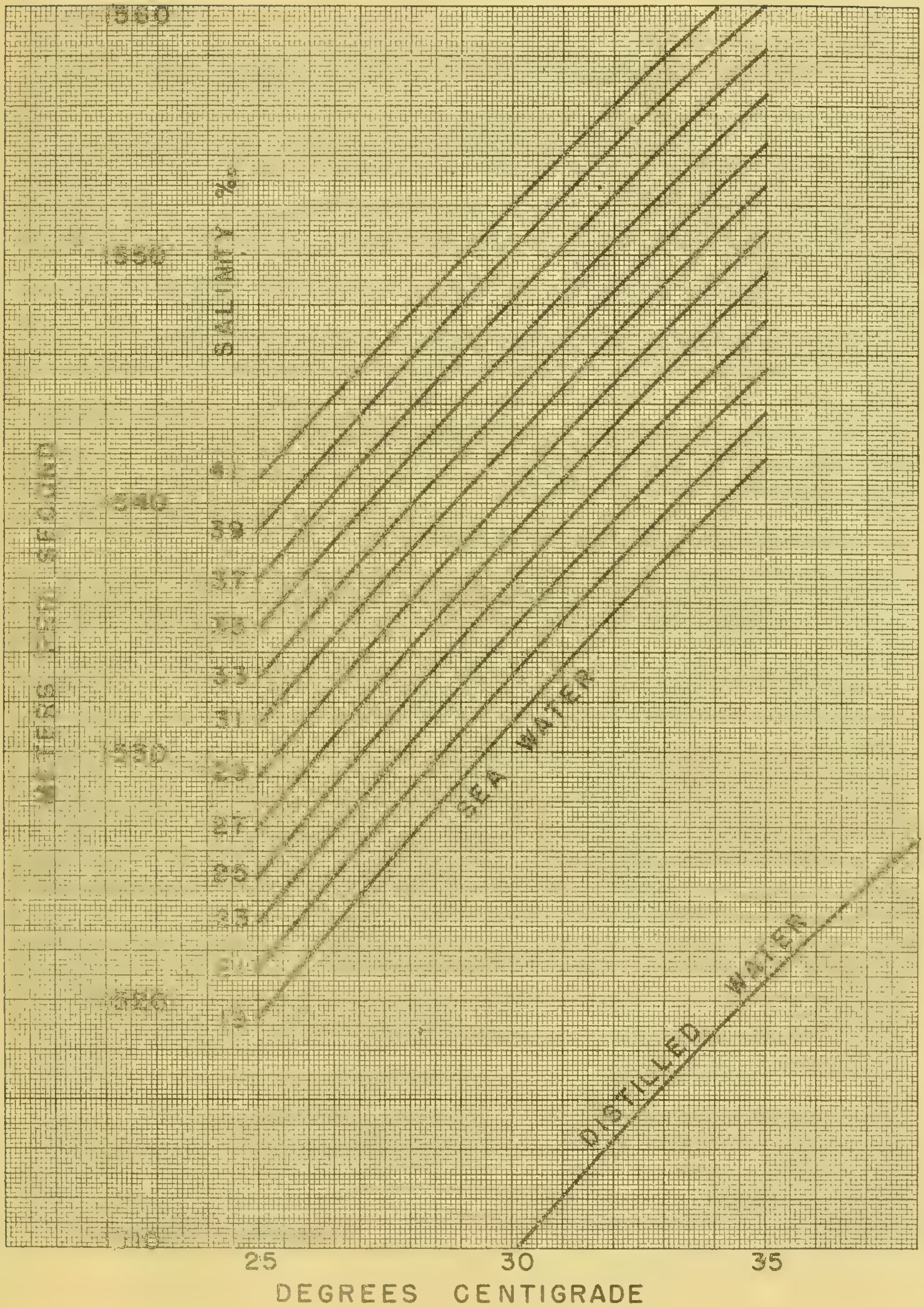
SALINITY ‰
39
25
SEA WATER
DISTILLED WATER
25
30
35
DEGREES CENTIGRADE

Figure 1-f

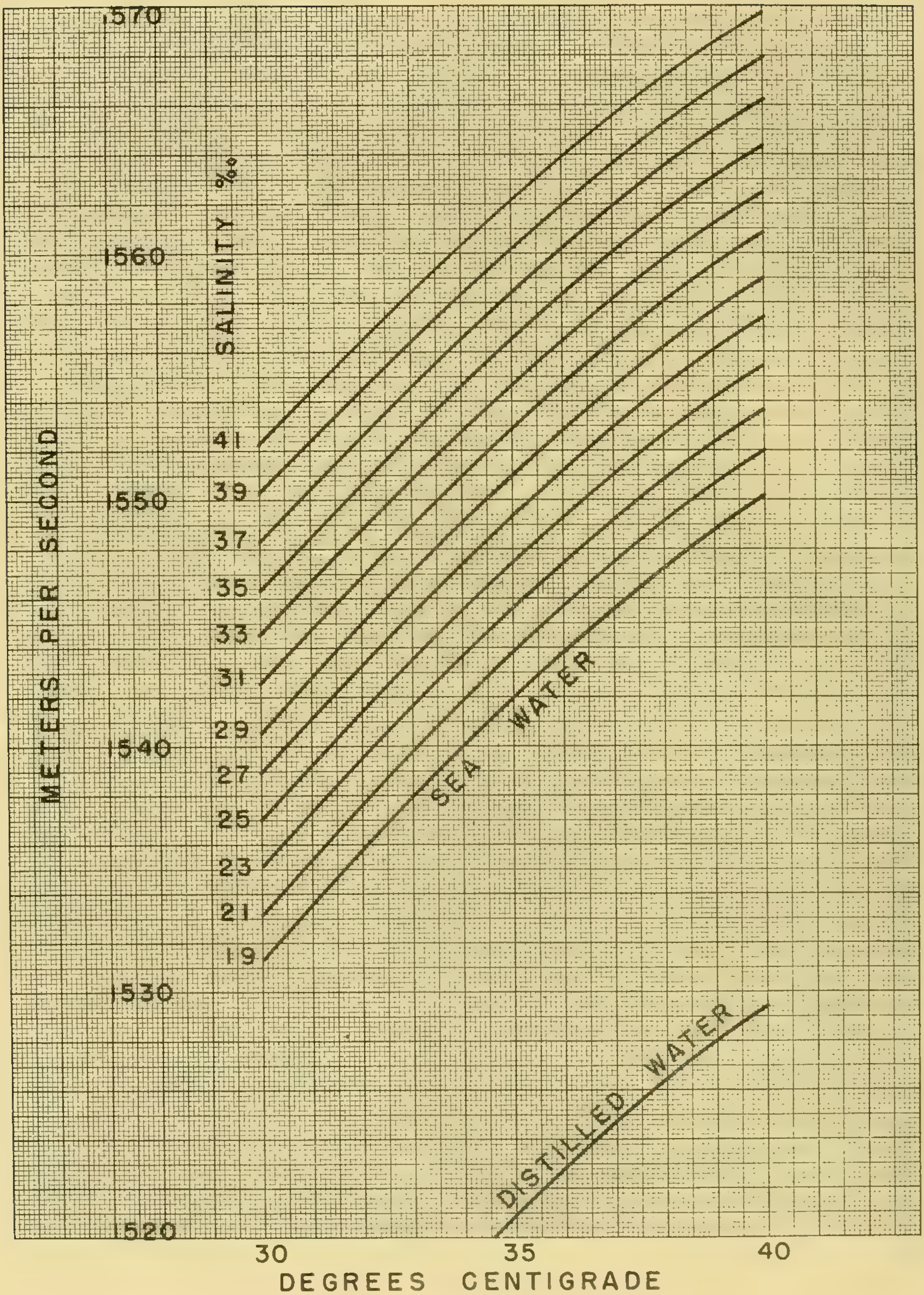
1570
1560
1550
1540
1530
1520
METERS PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
DISTILLED WATER
30
35
40
DEGREES CENTIGRADE

Figure 1-g

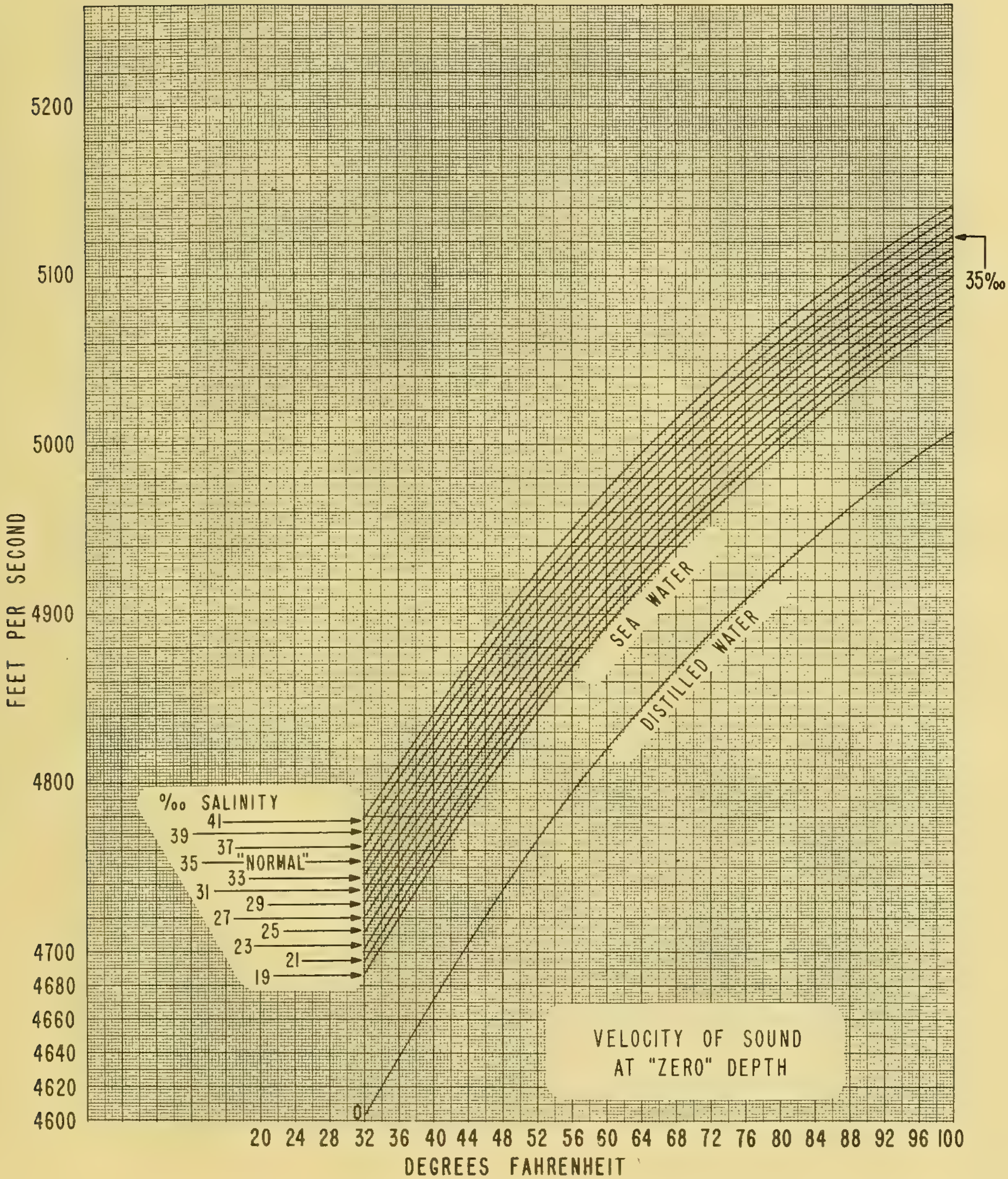

Figure 2 - Velocity of Sound at Zero Depth - British Units

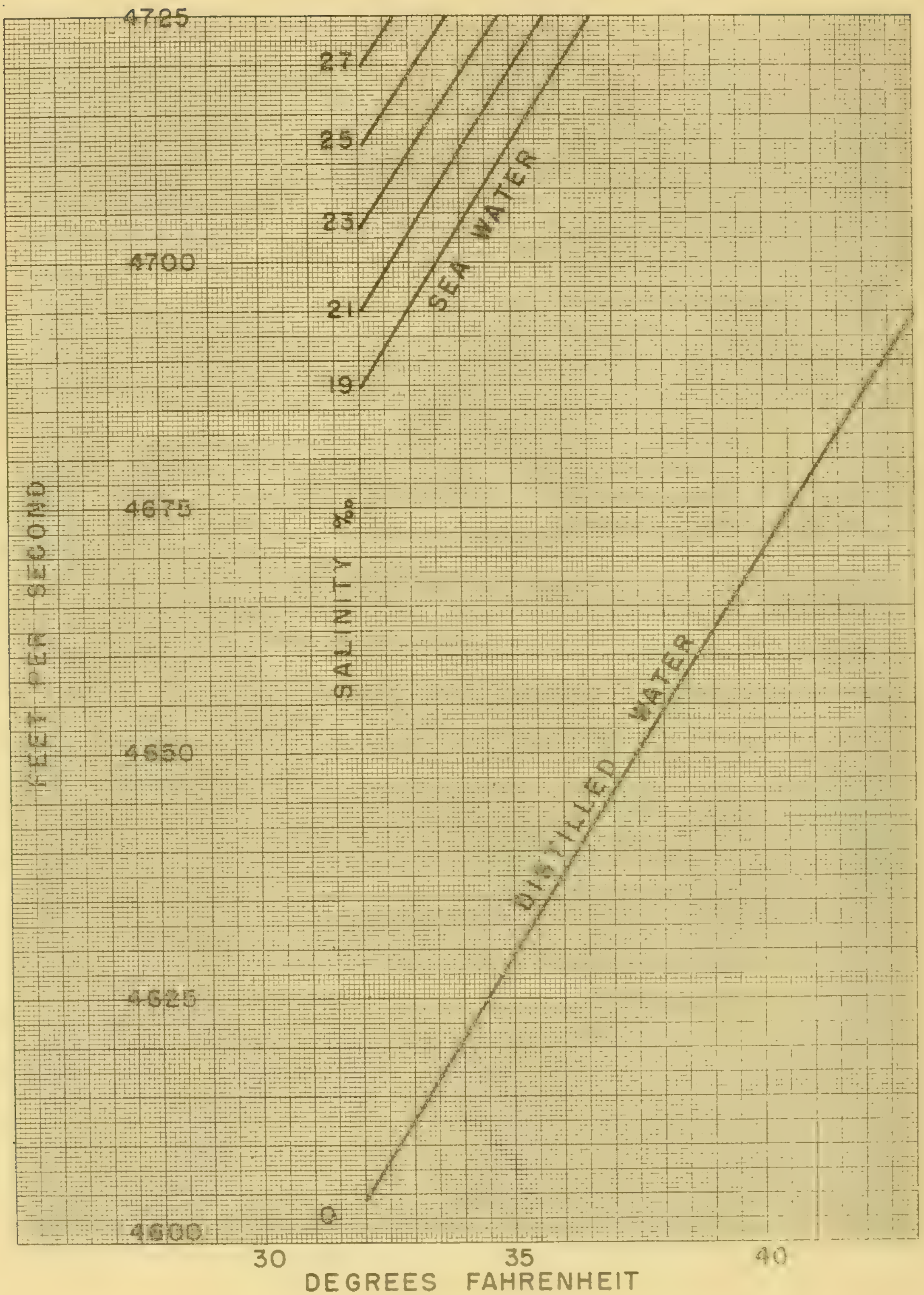

Figure 2-a

Figure 2 a-p.- Velocity of Sound at Zero Depth - British Units Expanded Scale

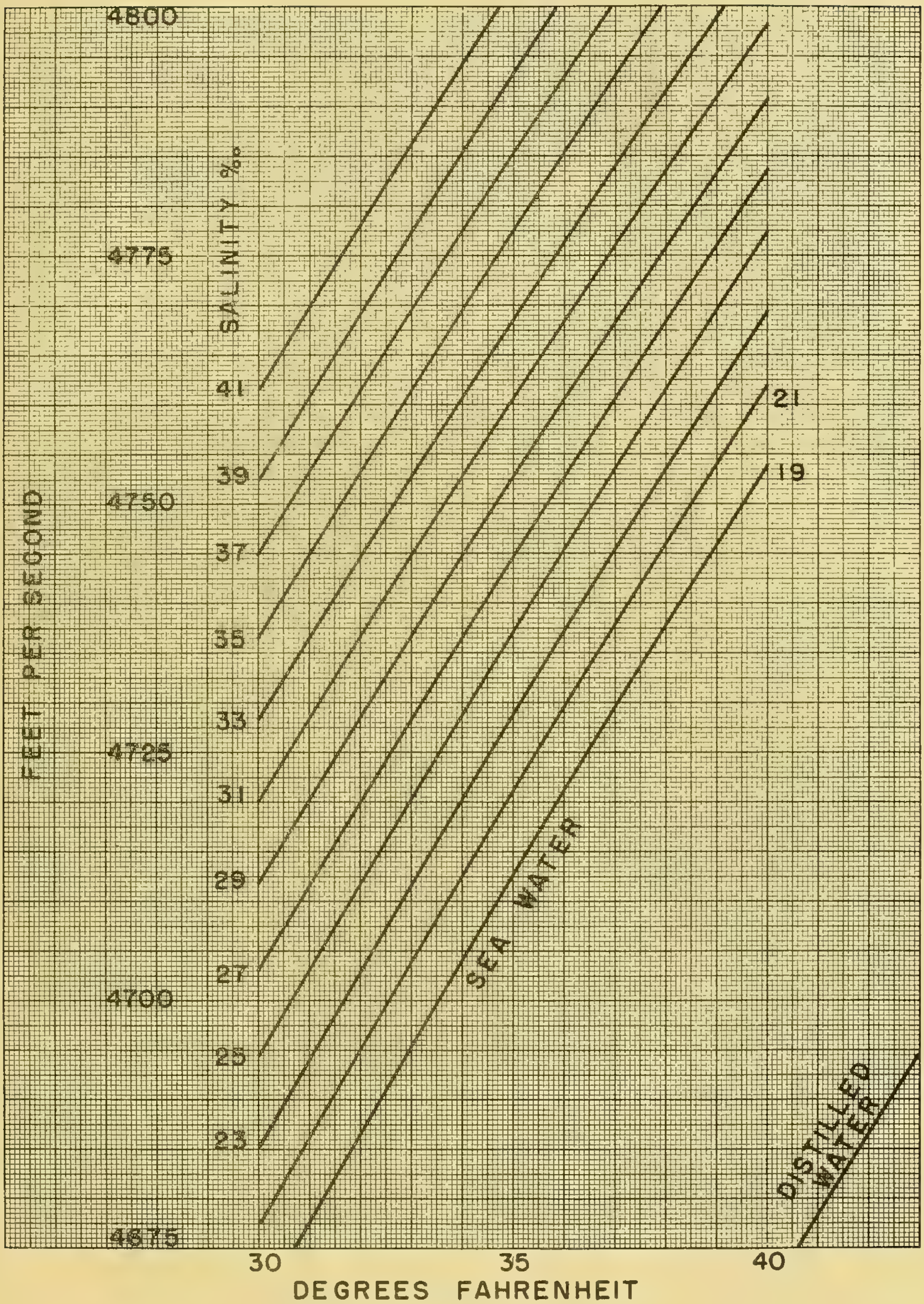
4800
4775
4750
4725
4700
4675
FEET PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
DISTILLED WATER
30
35
40
DEGREES FAHRENHEIT

Figure 2-b

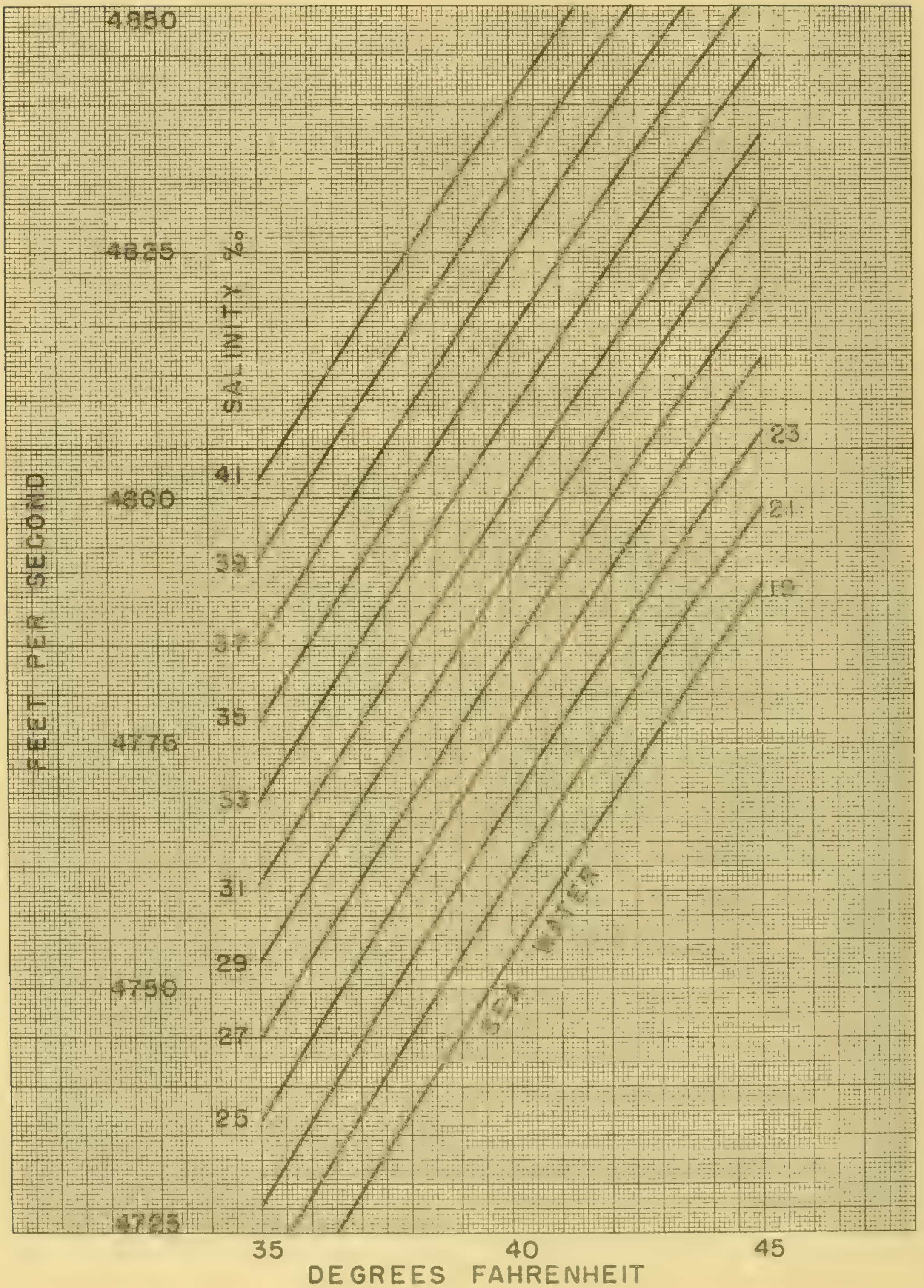
4850
4825
4800
4775
4750
4725
FEET PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
35
40
45
DEGREES FAHRENHEIT

Figure 2- c

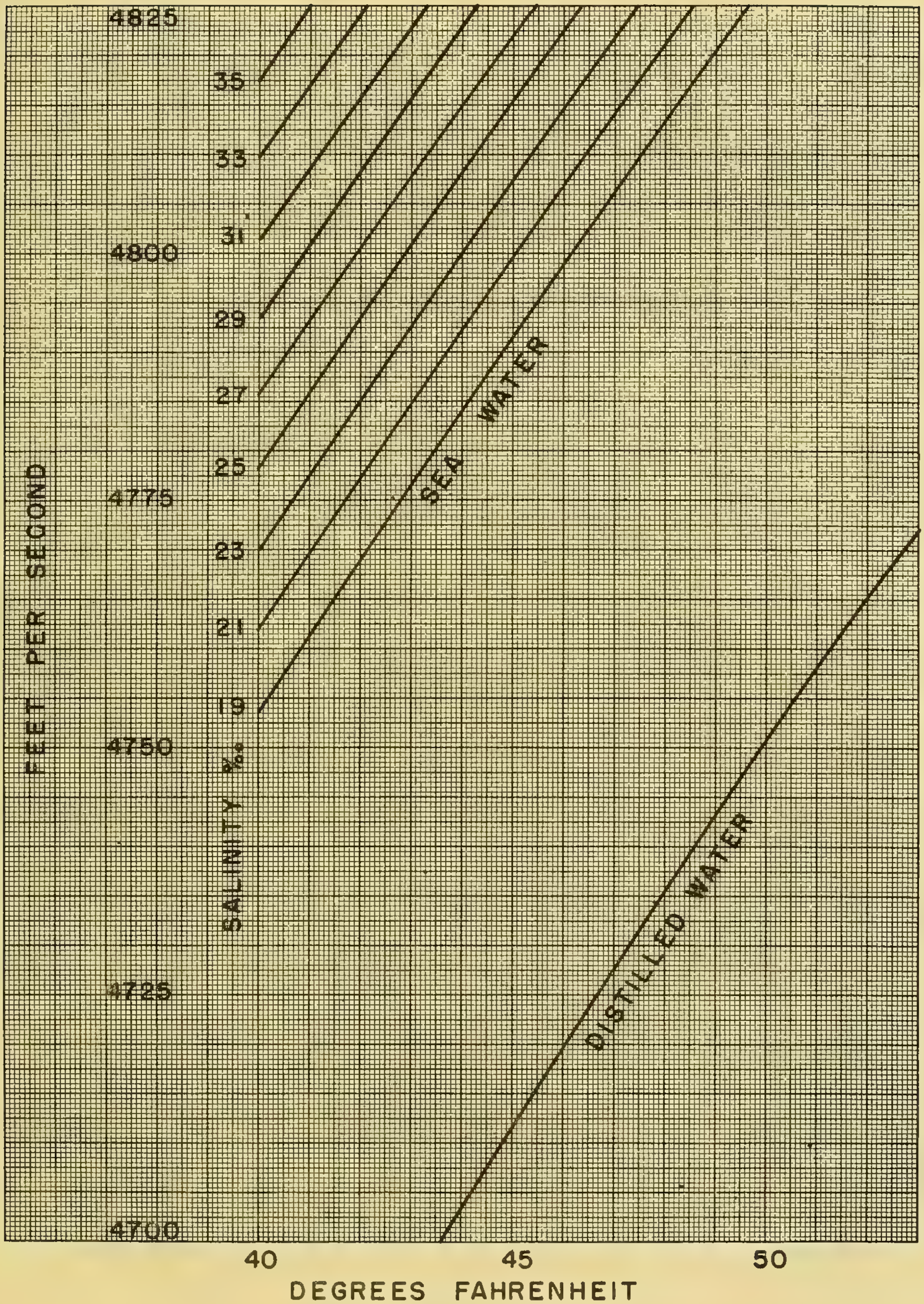
4825
4800
4775
4750
4725
4700
FEET PER SECOND
35
33
31
29
27
25
23
21
19
SALINITY ‰
SEA WATER
DISTILLED WATER
40
45
50
DEGREES FAHRENHEIT

Figure 2-d

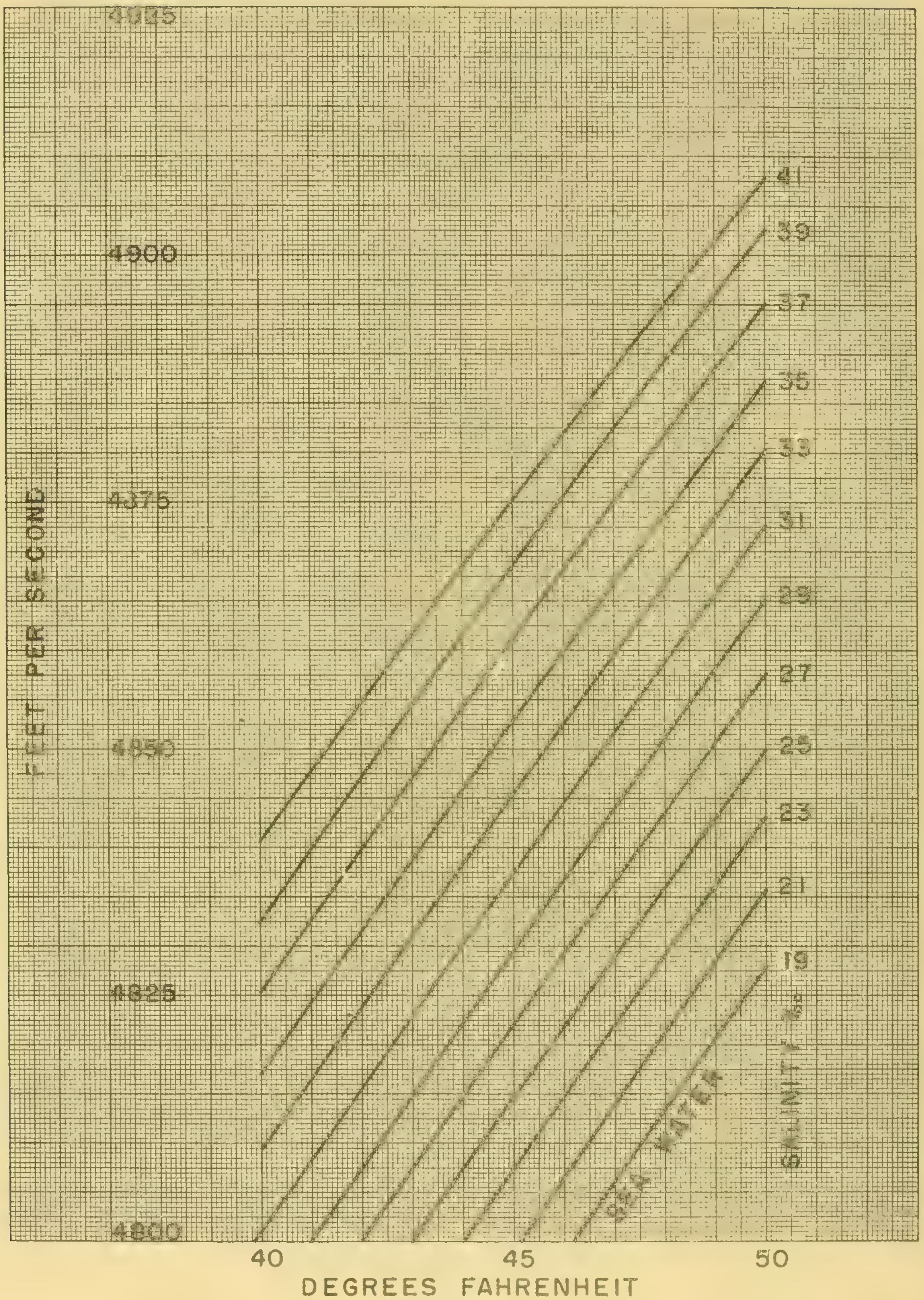
4925
4900
4875
4850
4825
4800
FEET PER SECOND
40
45
50
DEGREES FAHRENHEIT
41
39
37
35
33
31
29
27
25
23
21
19
SALINITY ‰
SEA WATER

Figure 2-e

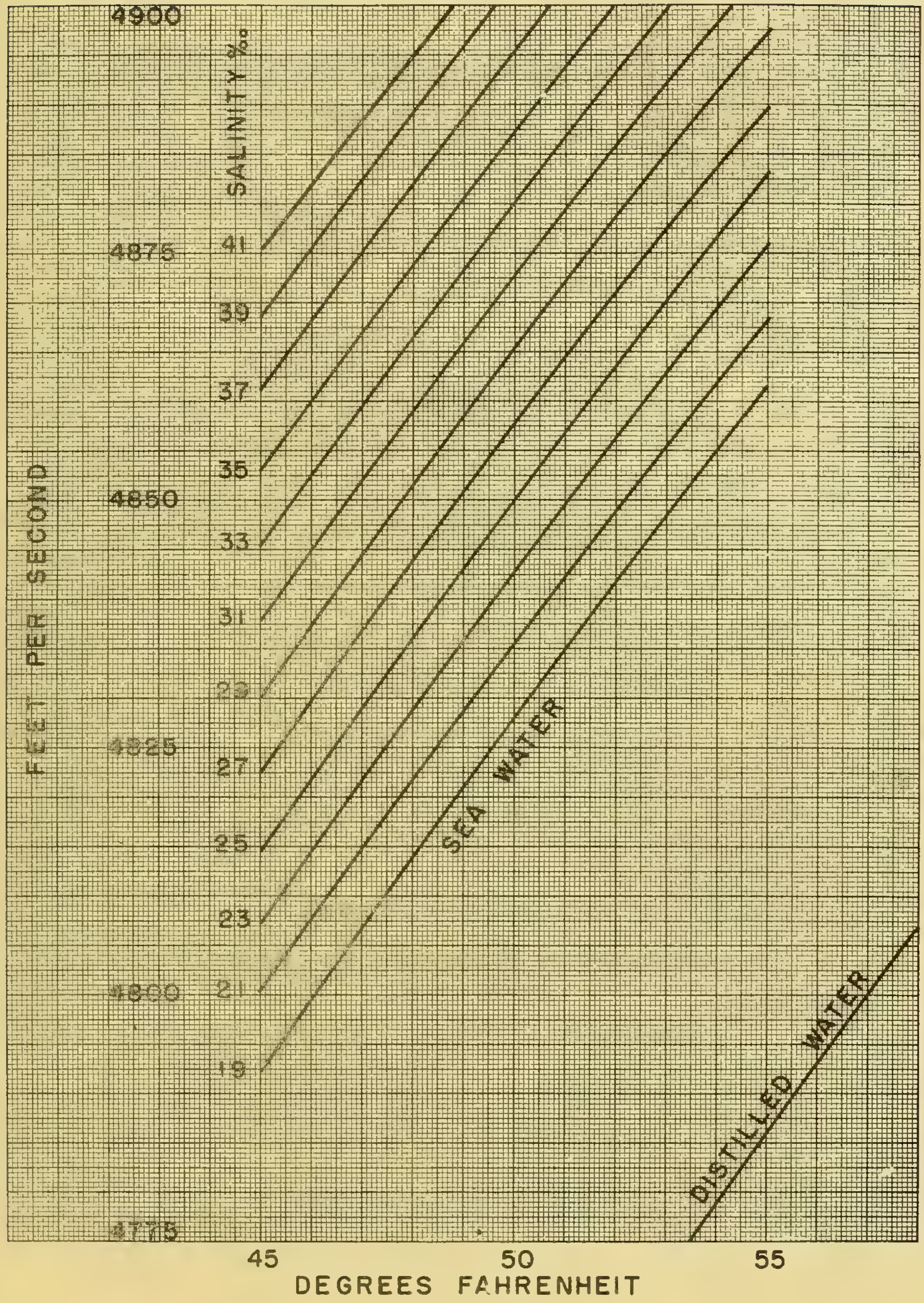
4900
4875
4850
4825
4800
4775
FEET PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
DISTILLED WATER
45
50
55
DEGREES FAHRENHEIT

Figure 2-f

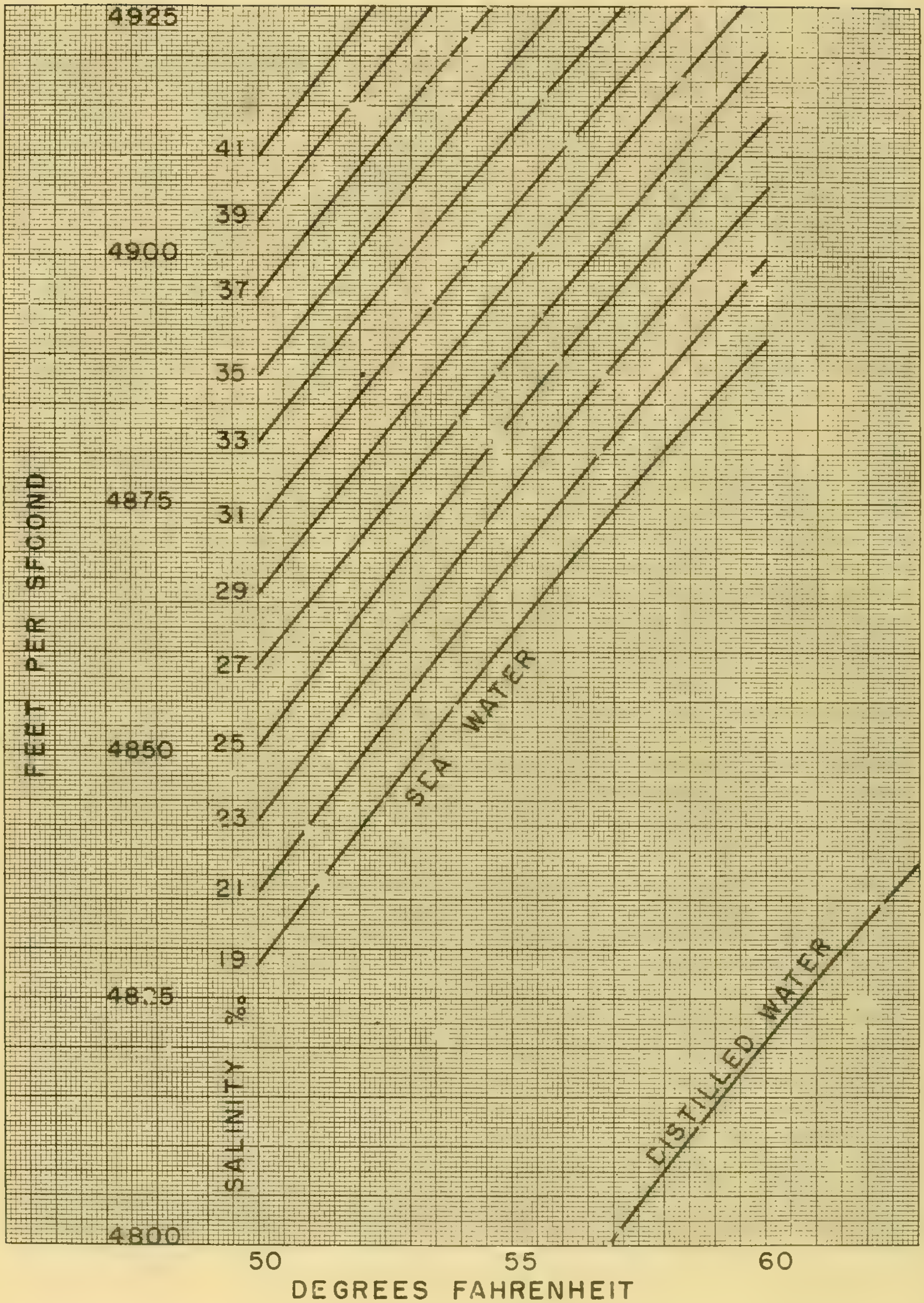
4925
4900
4875
4850
4825
4800
41
39
37
35
33
31
29
27
25
23
21
19
FEET PER SECOND
SALINITY ‰
SEA WATER
DISTILLED WATER
50
55
60
DEGREES FAHRENHEIT

Figure 2-g

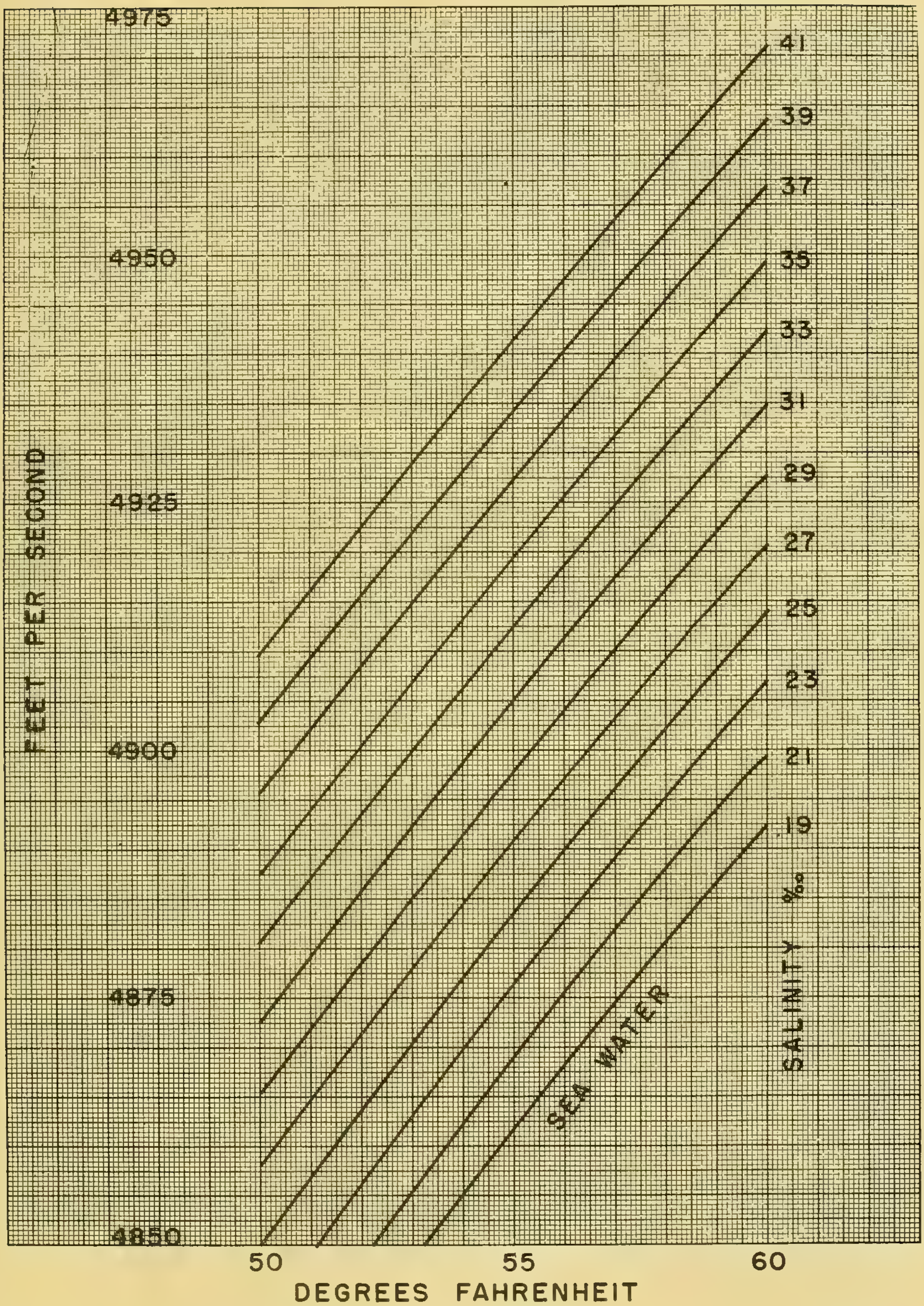
4975
4950
4925
4900
4875
4850
FEET PER SECOND
41
39
37
35
33
31
29
27
25
23
21
19
SALINITY ‰
SEA WATER
50
55
60
DEGREES FAHRENHEIT

Figure 2-h

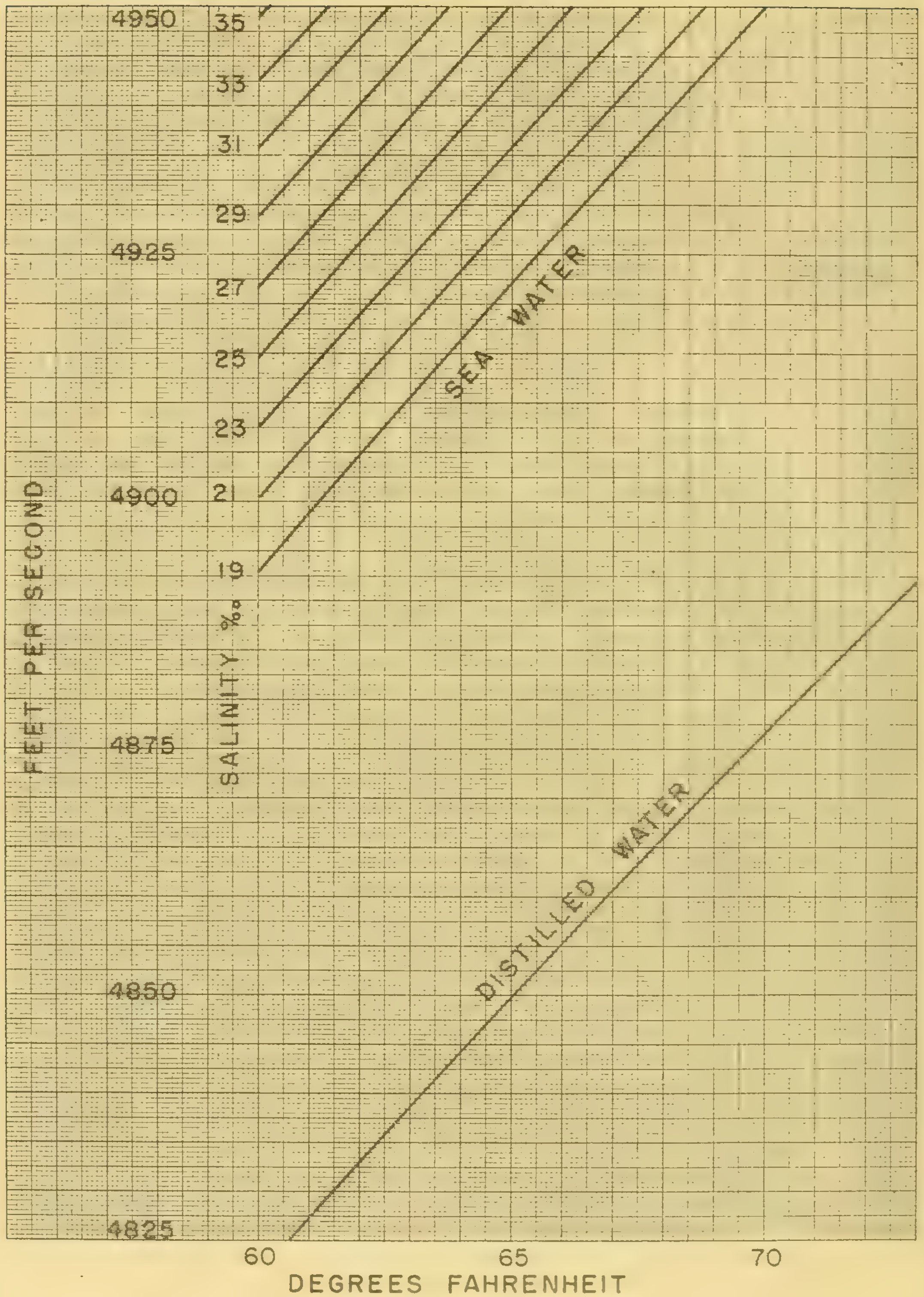
4950
4925
4900
4875
4850
4825
35
33
31
29
27
25
23
21
19
FEET PER SECOND
SALINITY ‰
SEA WATER
DISTILLED WATER
60
65
70
DEGREES FAHRENHEIT

Figure 2-i

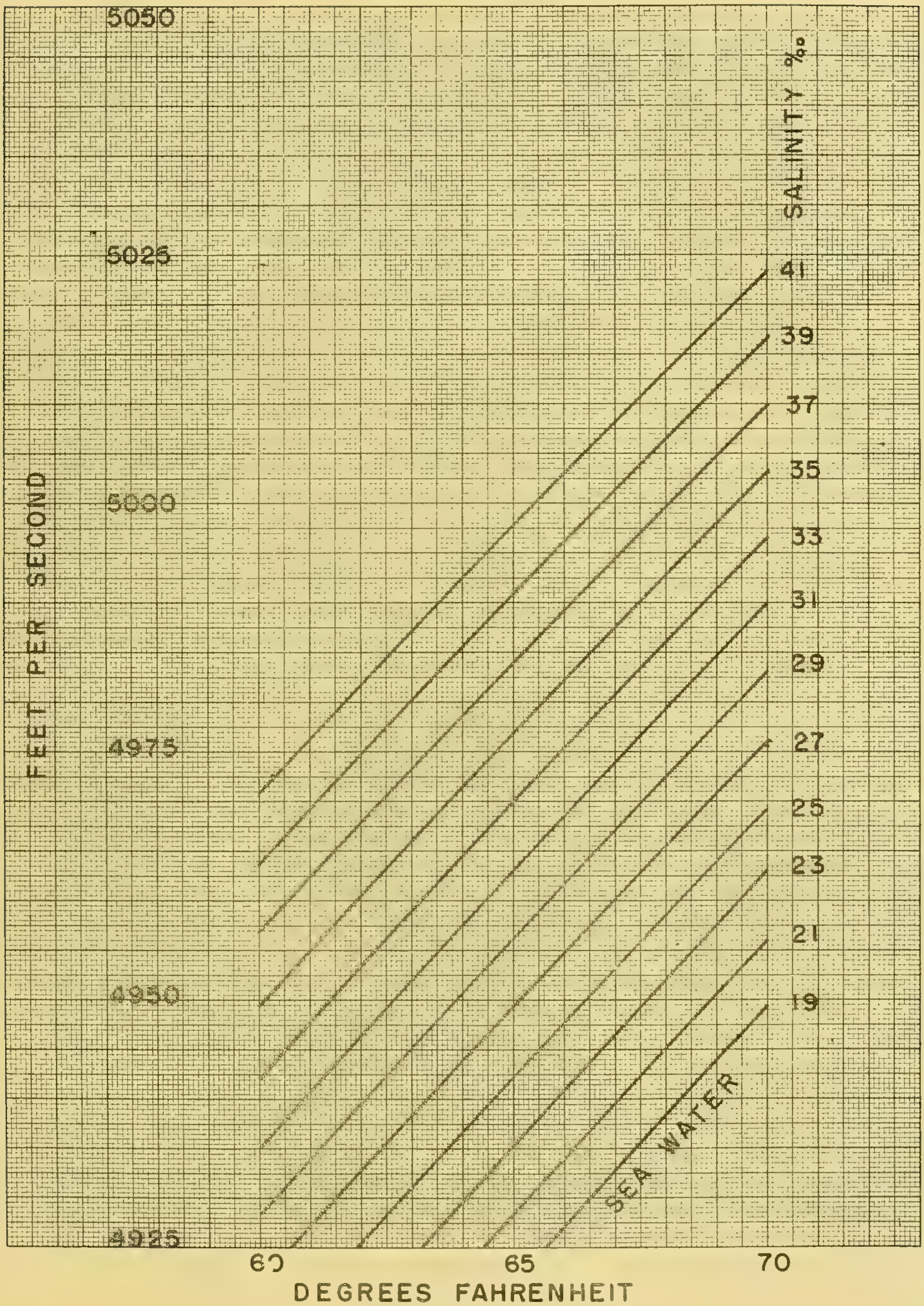
5050
5025
5000
4975
4950
4925
FEET PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
60
65
70
DEGREES FAHRENHEIT

Figure 2-j

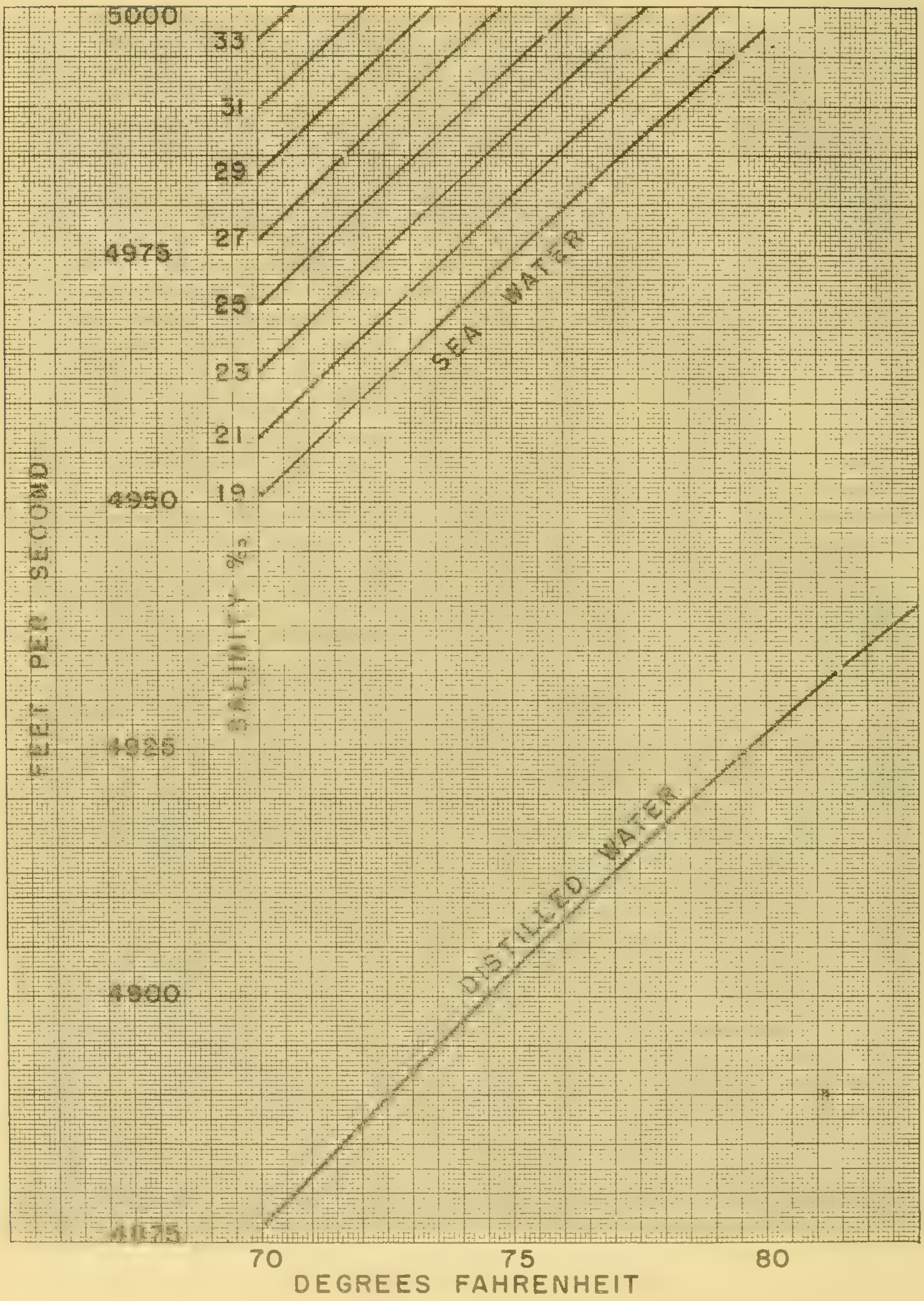
5000
4975
4950
4925
4900
4875
33
31
29
27
25
23
21
19
SALINITY ‰
SEA WATER
DISTILLED WATER
FEET PER SECOND
70
75
80
DEGREES FAHRENHEIT

Figure 2-k

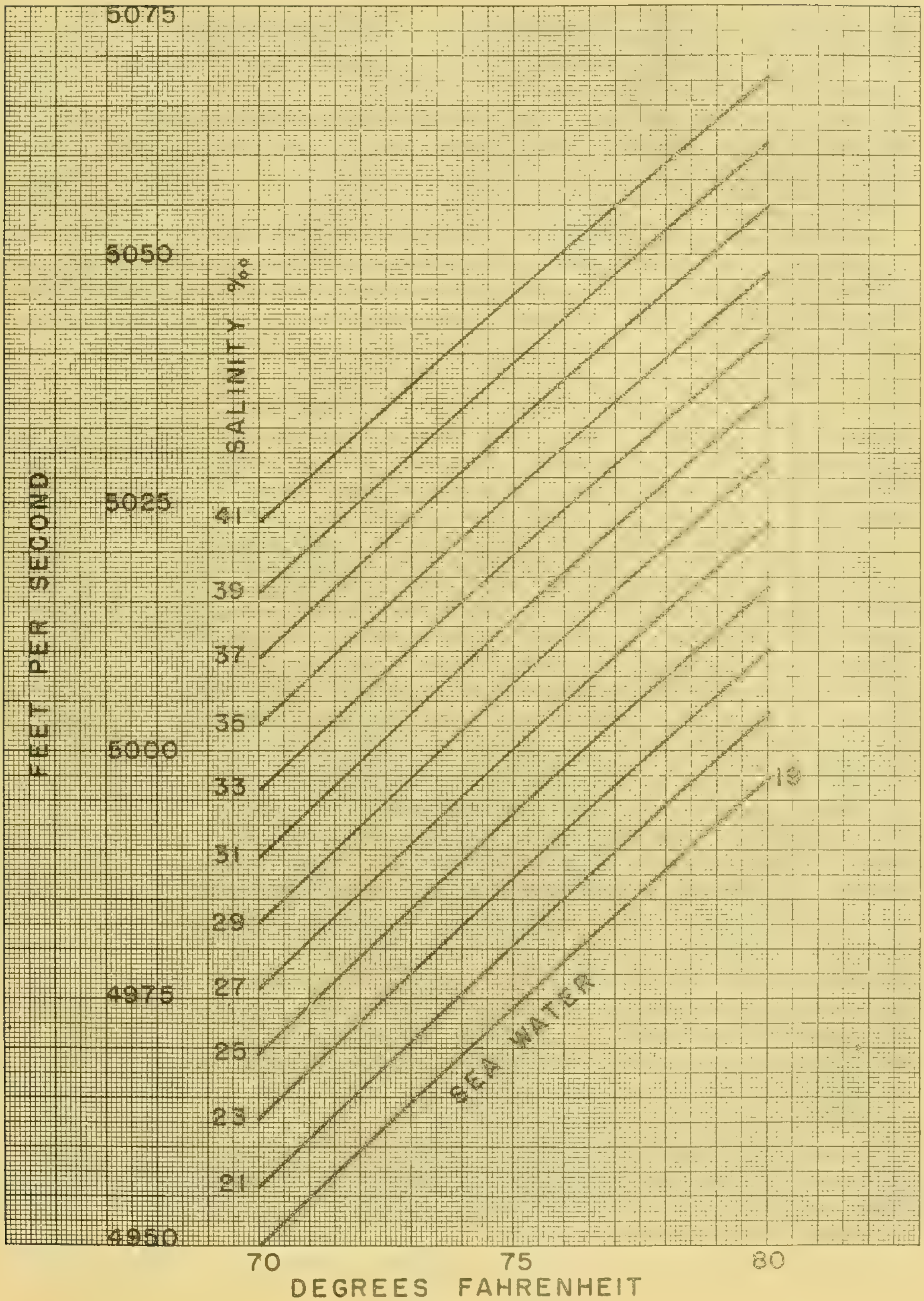
5075
5050
5025
5000
4975
4950
FEET PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
70
75
80
DEGREES FAHRENHEIT

Figure 2-1

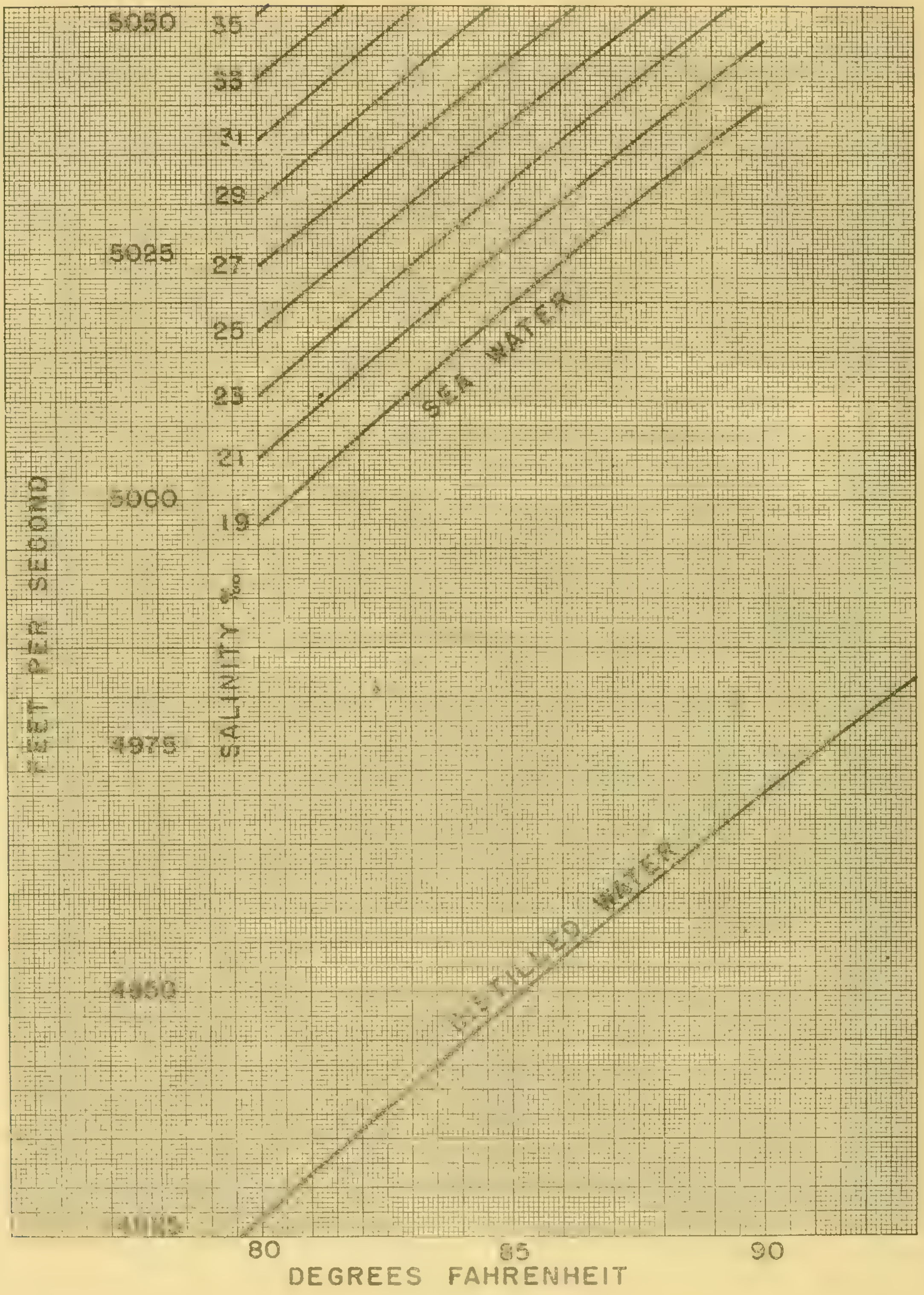
5050
5025
5000
4975
4950
FEET PER SECOND
35
33
31
29
27
25
23
21
19
SALINITY ‰
SEA WATER
DISTILLED WATER
80
85
90
DEGREES FAHRENHEIT

Figure 2-m

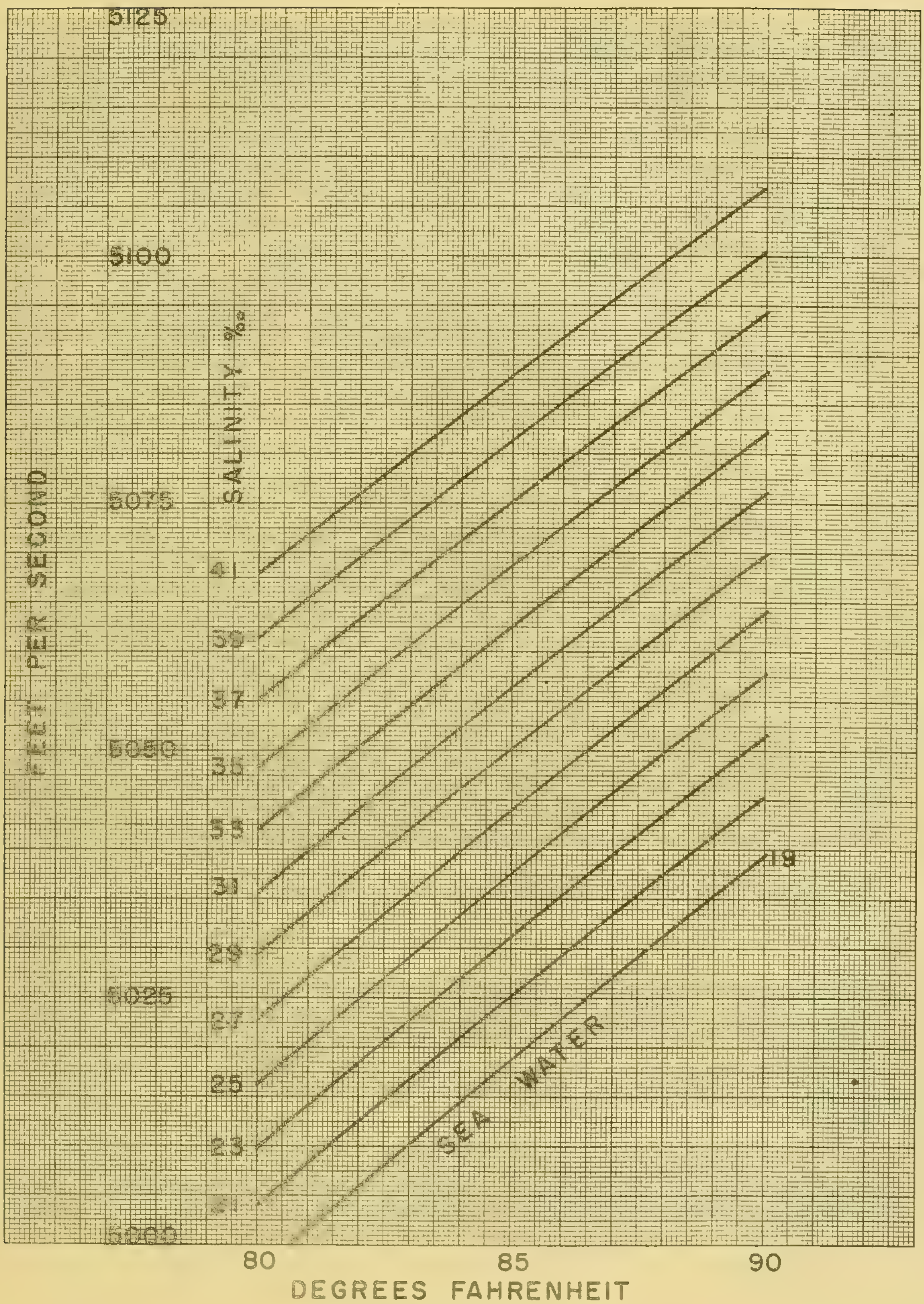
5125
5100
5075
5050
5025
5000
FEET PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
80
85
90
DEGREES FAHRENHEIT

Figure 2-n

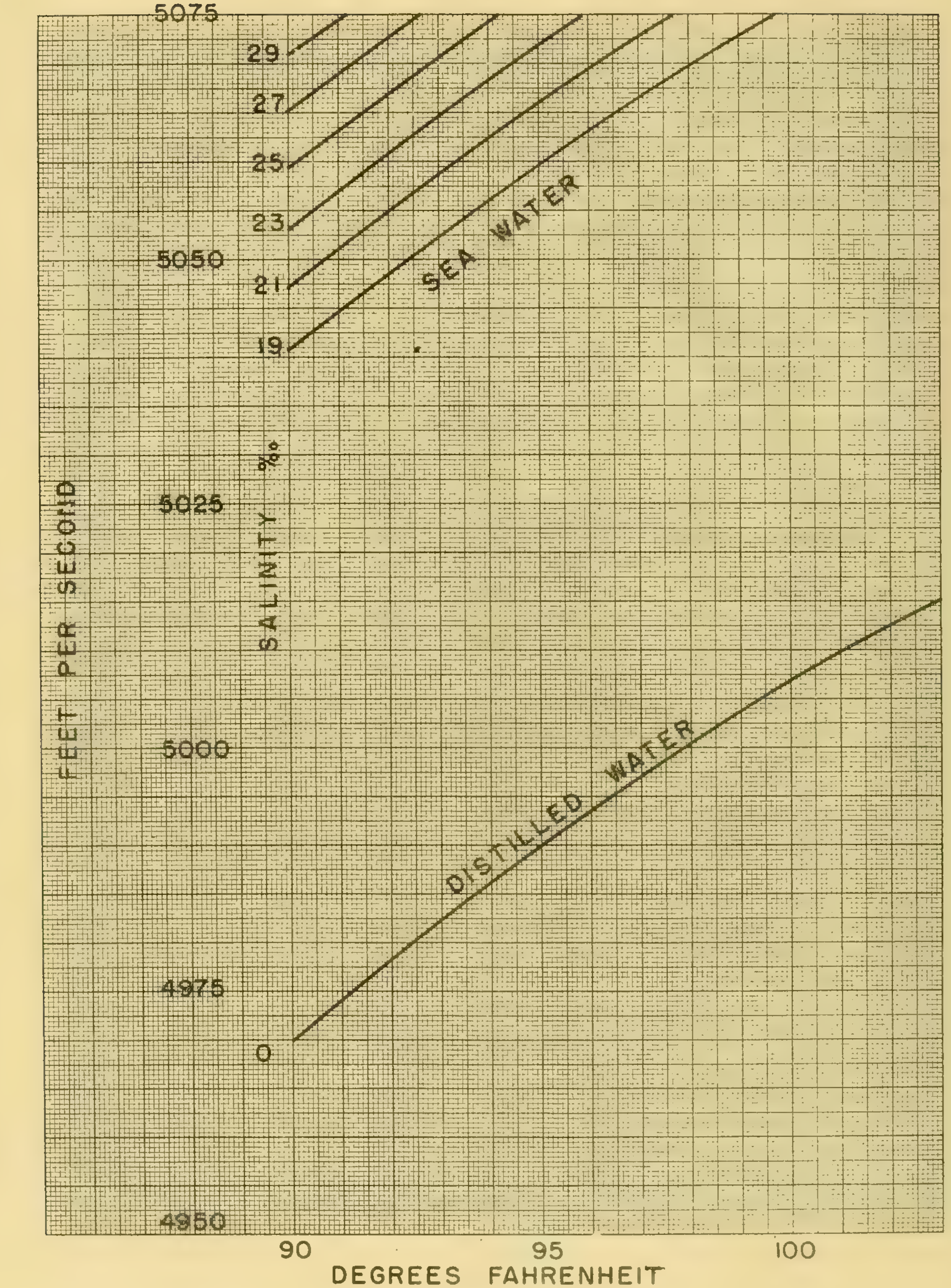
5075
5050
5025
5000
4975
4950
29
27
25
23
21
19
0
SEA WATER
DISTILLED WATER
FEET PER SECOND
SALINITY ‰
90
95
100
DEGREES FAHRENHEIT

Figure 2-o

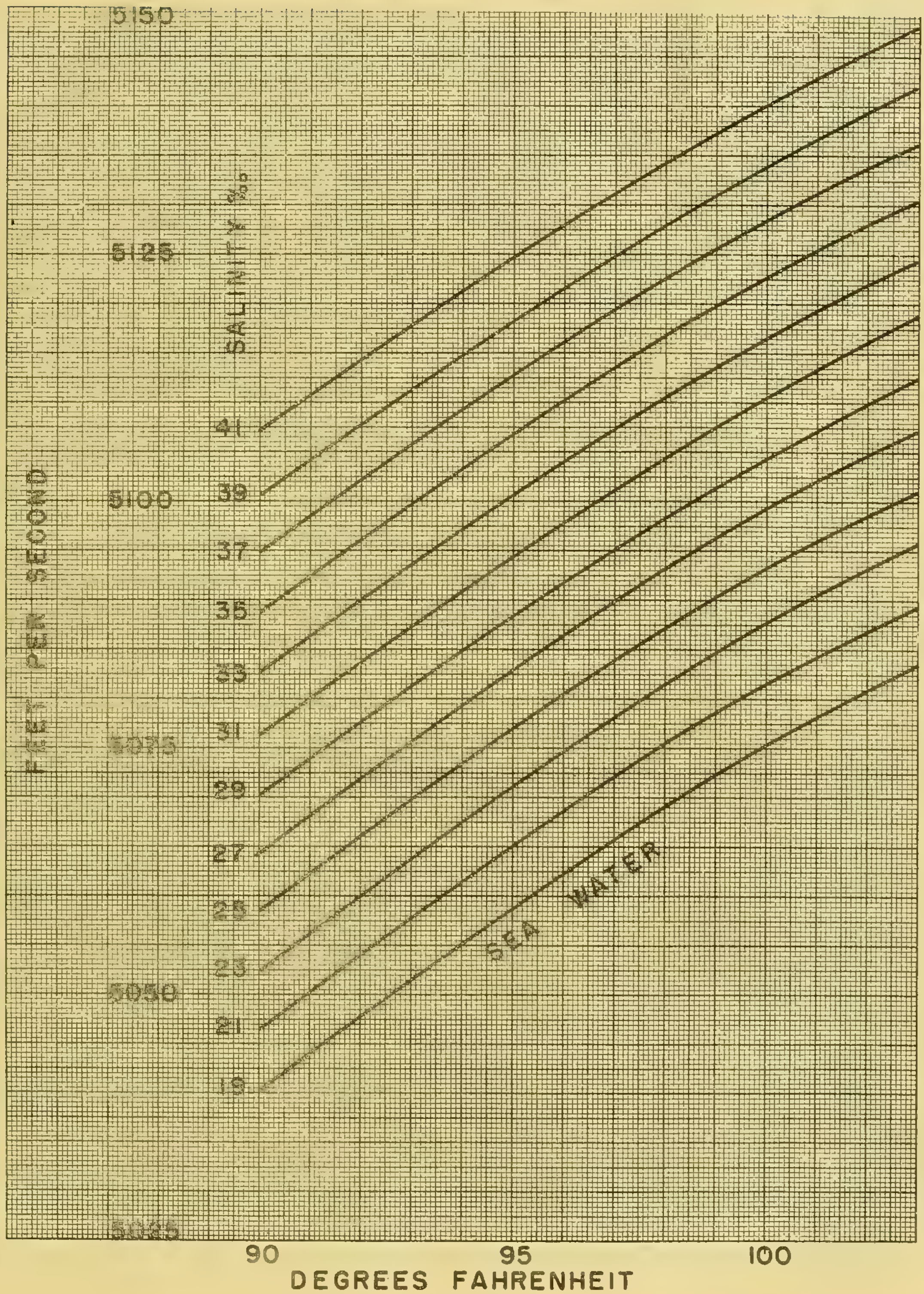
5150
5125
5100
5075
5050
5025
FEET PER SECOND
SALINITY ‰
41
39
37
35
33
31
29
27
25
23
21
19
SEA WATER
90
95
100
DEGREES FAHRENHEIT

Figure 2-p

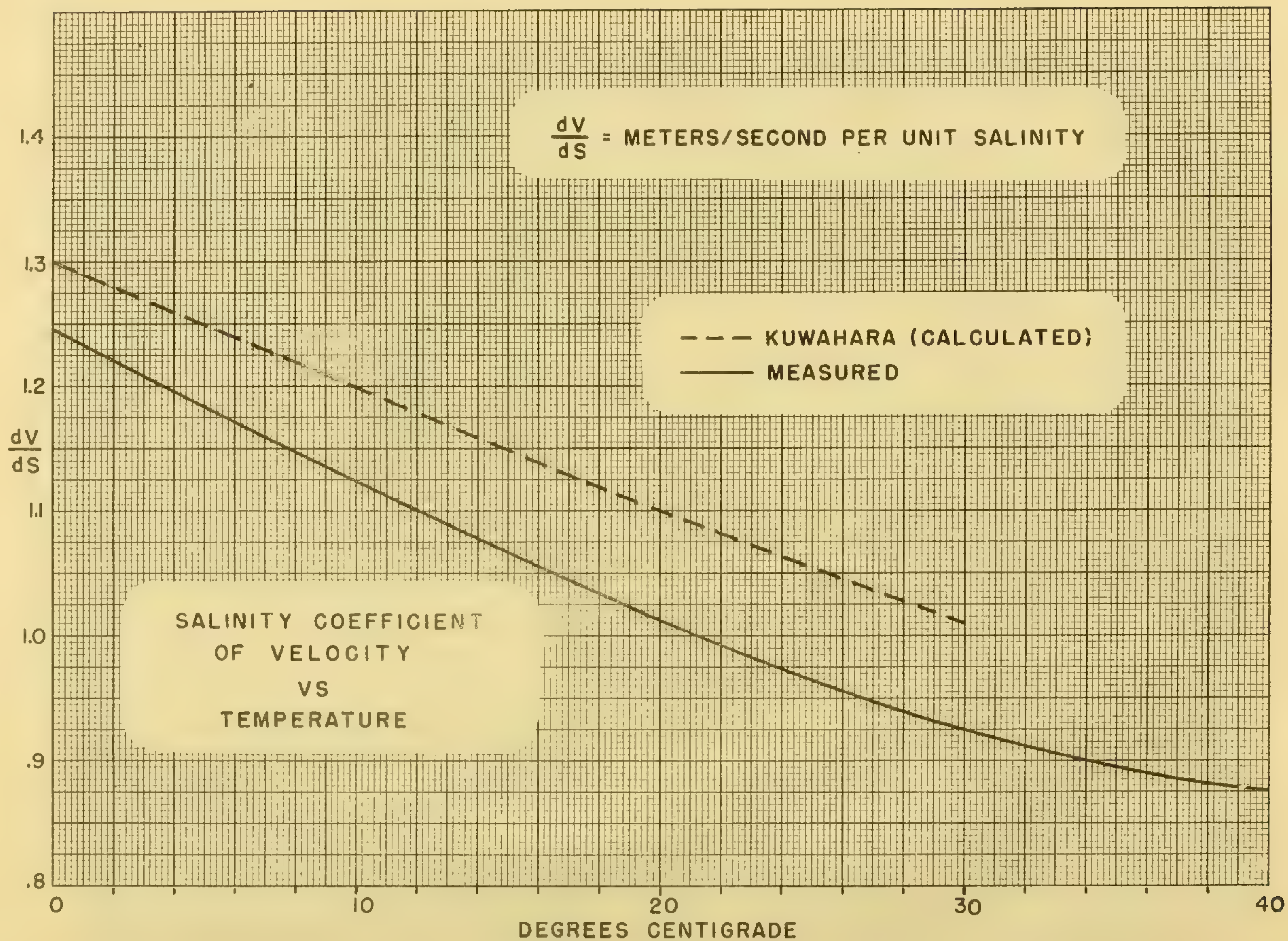

Figure 3 - Salinity Coefficient of Velocity vs. Temperature Metric Units

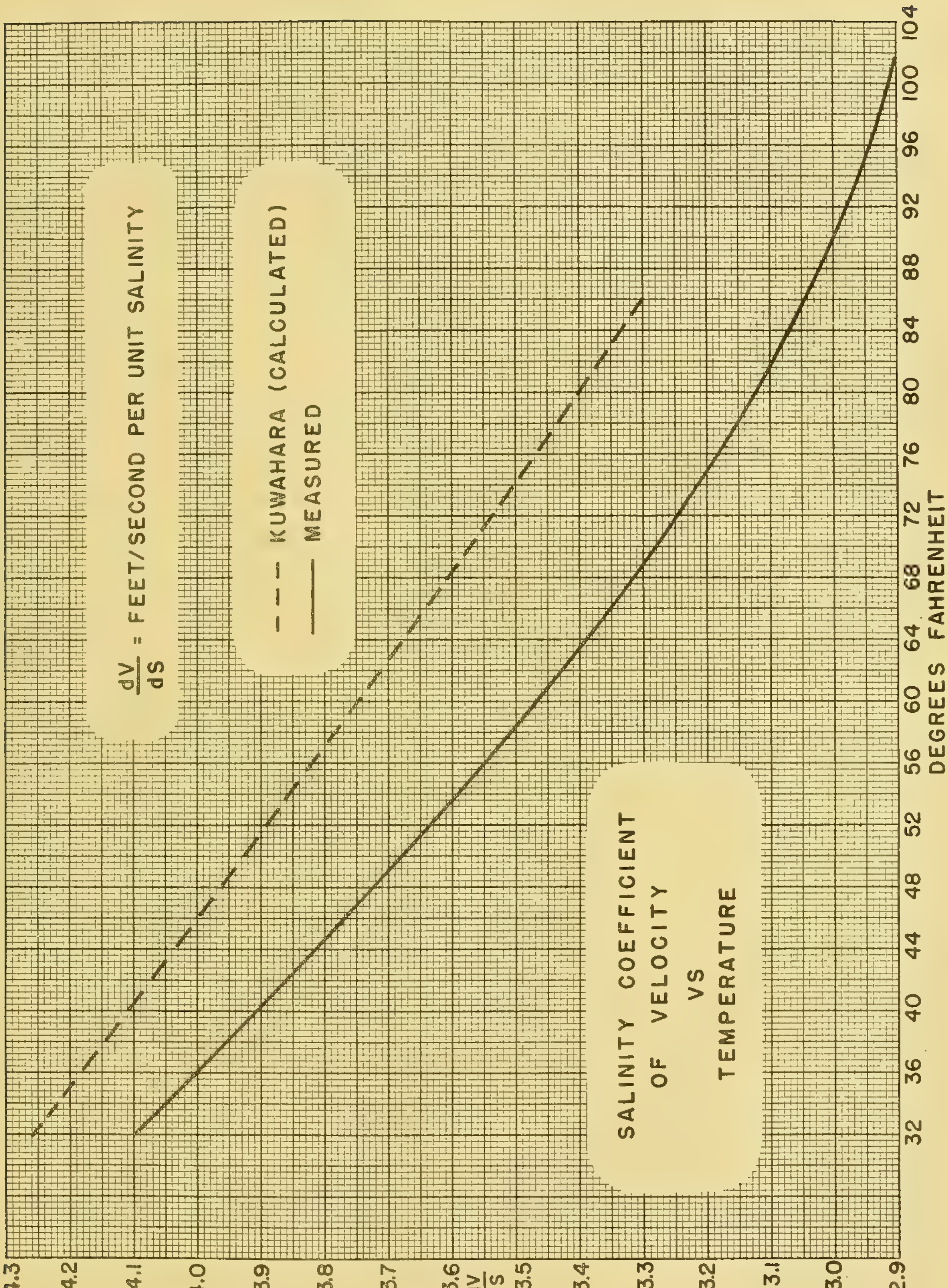

Figure 4 - Salinity Coefficient of Velocity vs. Temperature British Units

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